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**The Sliding Rocks of Racetrack Playa, Death Valley
National Park, California: Physical and Spatial
Influences on Surface Processes**

by

PAULA MESSINA

A dissertation submitted to the Graduate Faculty in Earth and Environmental Sciences in
partial fulfillment of the requirements for the degree of Doctor of Philosophy, the City
University of New York

1998

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THE CITY UNIVERSITY OF NEW YORK

Abstract

THE SLIDING ROCKS OF RACETRACK PLAYA, DEATH VALLEY NATIONAL PARK, CALIFORNIA: PHYSICAL AND SPATIAL INFLUENCES ON SURFACE PROCESSES

by Paula Messina

Adviser: Professor Keith C. Clarke

The Racetrack is a dry lakebed nestled within the Panamint Range in Death Valley National Park, California. Though almost perfectly flat, it shows evidence of dynamic traction events of boulder-sized and smaller rock fragments that tumble onto it from two abutting cliffs and surrounding alluvial fans. Scars of sliding rock activity in the form of recessed furrows have been noted since the beginning of the twentieth century, yet to date no one has witnessed the actual surface process causing the rocks to slide.

The location of every rock and its associated trail was recorded using Differential Global Positioning System (DGPS) and Geographic Information System (GIS) methods in July, 1996. The resulting map shows a total of 162 rocks and trails to a horizontal accuracy of about 30 centimeters.

Examination of trail patterns shows an inferred general trend in rock movement toward the north-northeast. This is consistent with the direction of prevailing winds. However, there is a high degree of variation in trail character. Surprisingly, trail lengths and headings are not well correlated with rock shape, volume or surface-contact area.

Analyses conducted on the digital data set show that large rocks tend to produce shorter, straighter trails. However, a rock's total distance traveled and the degree to which it follows a straight-line path is more significantly influenced by its location on the playa

at the onset of motion.

The Racetrack's southeastern sector, about 5 centimeters lower in elevation, is more frequently saturated by collecting rain water. In addition, the presence of three natural springs may contribute to lower friction coefficients in this region. The longest and straightest trails are preferentially distributed in the southeast, as rocks are propelled by the amplified force of horizontal winds when air is channeled through one of two topographic corridors to the south. The central part of the playa is a focal point for two such natural wind tunnels. In this part of the playa, trails are most convoluted, suggesting entrainment of rocks in wind vortices. This research quantifies the influence of the surrounding topography on inferred airflow, ultimately governing the nature and magnitude of sliding rock episodes.

Acknowledgments

The challenges of this research project would not have been overcome without the assistance and generosity of several people. Without question, Phil Stoffer (my field partner, research assistant, fellow graduate student and husband) deserves the highest commendation for his selfless reassurance and limitless patience. Without his help, which included several cross-country trips to one of the most inhospitable places on Earth, the field work necessary to complete this research would have been impossible.

I extend my heartfelt gratitude to Professor Keith C. Clarke whose encouragement, unwavering optimism and enthusiasm for this project, from its very beginnings, have been inspirational to me. Thanks are also extended to Professors Victor Goldsmith, John A. Chamberlain and Detlef Warnke, who have been tremendously helpful not only in their academic advisement but also in their personal candor. I deeply appreciate the support of Professors Sean Ahearn and Peter Combs of Hunter College for their informal advice. Without the assistance of Tom Walter (Hunter College) and Mark Probert (University of California, Santa Barbara), many of the computer operations conducted in this research would have been unachievable. Professor Karen Mulcahy (University of East Carolina) donated several hours of her time to provide Arc/Info- and other technical-assistance; Doug Williamson (Hunter College) offered his expertise numerous times as well. Tony Grande (Hunter College) and Lina McClain (City University Graduate Center) are invaluable assets to their programs and students.

It has been a delight to converse and correspond with Dr. Robert P. Sharp (California Institute of Technology), author of one of the pivotal papers on this unusual phenome-

non. It is an honor to know him; I relish his anecdotes, and cherish his advice.

I thank Death Valley National Park for allowing me to conduct this research. I especially appreciate the assistance of Richard Anderson (Resources Management), Roger Brandt, Dan Dellinges and Kevin Emmerich. John Vogel of the U.S. Geological Survey conducted numerous searches for maps, data and other related government documents.

Upon visiting the Racetrack Playa for the first time, a friend, Mary Pat Hepp, suggested studying the isolated and unusual locality for my doctoral research, so I owe much to her. Since then, many friends have contributed in less tangible ways, but their support is no less treasured; thanks to Gary Horowitz, Diane Zizak, Paul Speranza and Bob Palestino. As a bi-coastal, multi-campus project, I also wish to thank those who helped me feel at home in California: Margot Clarke, Helmut Ehrenspeck, Jeannette Candau, David Lawson, Tacy Costanza, Tracy Ruge.

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Chapter 1

Regional Setting and Natural History

1.1 Physical Geography

The name “Death Valley” refers to both a topographic basin in California, and the surrounding 13,000 square kilometer National Park (see Figure 1.1, page 2). Best known for topographic and climatic extremes, the park contains the lowest points in the Western Hemisphere (at an elevation of -86 meters), at Badwater, California. The valley also boasts the highest recorded air temperature in the Western Hemisphere (57°C), a distinction that has remained unchallenged since July 1913. Ground temperatures of 94°C were recorded at Furnace Creek on July 15, 1972. In the rain shadow of the Sierra Nevada Mountains, the valley floor averages under 5 centimeters of precipitation per year. Yet despite its well-known and often inhospitable physical conditions, it is also a place of great topographic relief with its highest point, Telescope Peak, at 3370 meters. The relief results in an impressive thermal gradient with correspondingly dynamic convective and orographic wind fields.

The landscape of the Death Valley region reflects the interaction of ongoing regional tectonism with Quaternary climatic processes. Recent shear and extensional activity have caused the normal faulting of north-south striking blocks, producing deep basins (such as Death Valley) and topographic ridges (such as the Sierra Nevada). Mt.

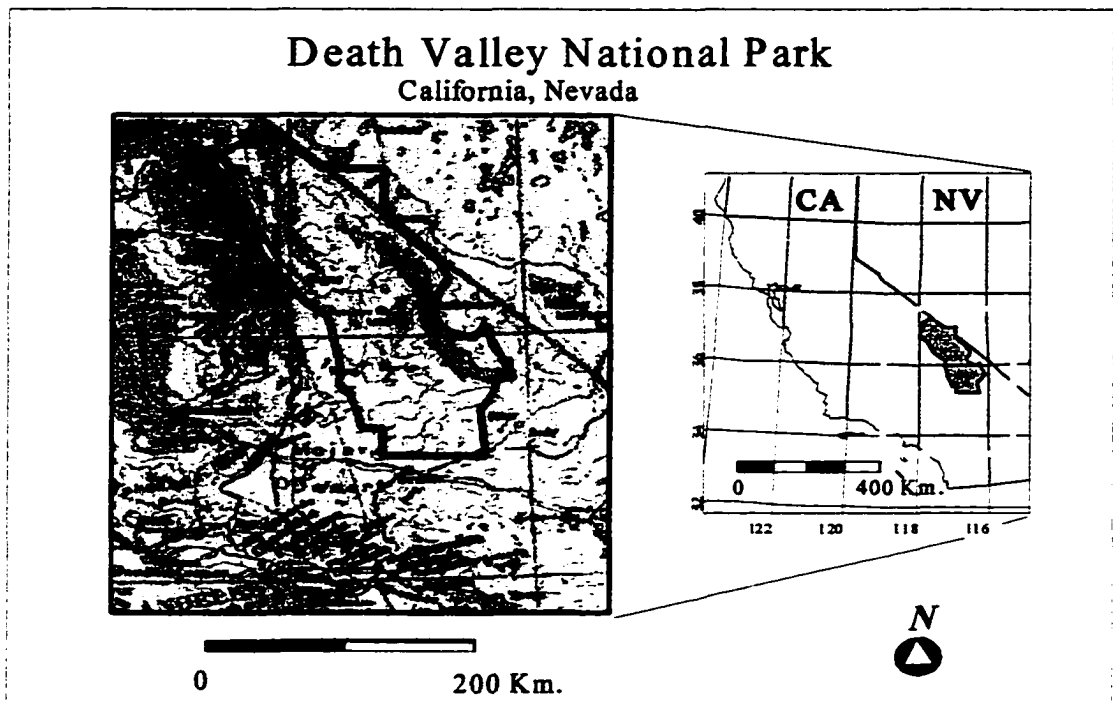


Figure 1.1: Death Valley National Park, locator map.

Whitney, at 4418 meters, is the highest mountain in the lower 48 states yet it lies a mere 130 kilometers west of Badwater. Before the most recent pulse of the Sierra Nevada uplift, the valleys to the east were flooded with water.

However, where perennial lakes used to exist, only hard-baked clay and evaporite deposits serve as reminders of the past climate. The Racetrack is one of these dry lake beds: a “ghost” of a body of water that persisted through the Pleistocene. Even during the Holocene, as recently as from 5000 to 2000 years ago, a shallow lake filled the Racetrack Basin (Hunt, 1975).

Playas such as this one dot the Basin and Range Physiographic Province as vestiges of cooler and wetter climates. The dry surface of Racetrack Playa, nestled within the Panamint Range, is at an elevation of 1131 meters; the surrounding mountains rise to

over 1710 meters (Figure 1.2). A hydrologically-closed basin, the valley encompasses a drainage area of about 180 square kilometers. It is estimated that more than three-quarters of the total drainage goes into the north end of the playa (Stanley, 1955). An encroaching alluvial fan at the south end of the valley cuts off surface drainage in that direction. Water also drains by subsurface flow into surrounding valleys (Hidden Valley, Saline Valley, etc.). Since no meteorological records exist it can only be inferred that the playa receives about 7 to 10 centimeters of precipitation per year, nearly double the total for Death Valley (Sharp and Carey, 1976).

Witnessed accounts of rain and ice accumulations are rare but date back to 1906 when a prospector named Joseph Crook reported about one centimeter of ice on the Race-

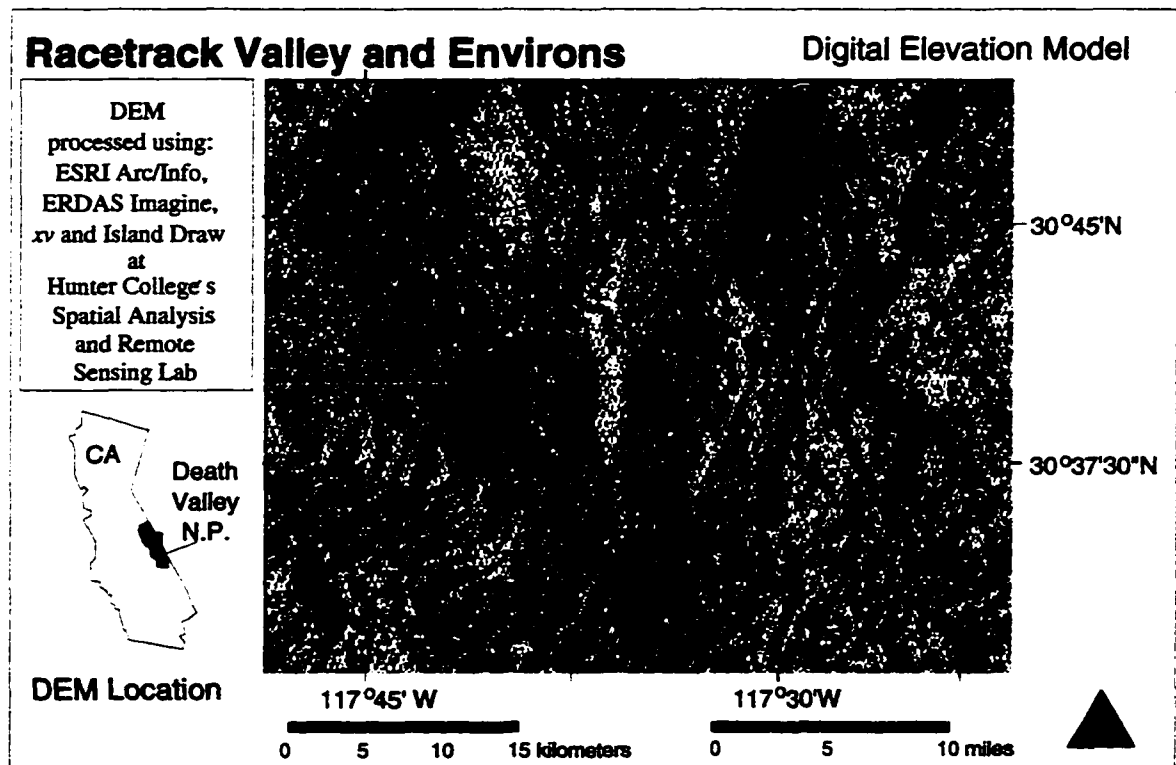


Figure 1.2: Hillshaded relief map of the Racetrack Basin and surrounding areas. Based on the 1-degree USGS Death Valley West digital elevation model.

track. McAllister encountered an expansive ice sheet on the surface for several weeks during the winter of 1947-1948, and in January 1949 Stanley Jones drove his pickup truck over eight centimeters of solid ice that rested directly on the mud below (Stanley, 1955). Conditions such as these are unusual; the storm that spawned the 1949 ice sheet also deposited about 10 centimeters of snow in Death Valley itself (Stanley, 1955). Meteoric water enters the basin from the north, and accumulates toward the downslope south end of the playa. As much as 25 centimeters of water has been reported on the playa, with many periods of precipitation during the winters of 1951 and 1952; during that unusually wet winter, wind drove the ponding water to one end of the playa, where it stayed for the duration of the storm (Stanley, 1955). As much as 30 centimeters of snow has been observed on the basin floor after isolated winter storms (Sharp and Carey, 1976).

The Racetrack displays a surface typical of other playas in the Southwest with mud-cracked lacustrine sediments composed of 24% fine sand, 41% silt and 35% clay (Sharp and Carey, 1976). It is nearly flat. Based on measurements of water depth during wet periods, it is about 5 centimeters higher in the north than in the south. Its major north-south axis length is approximately 4.5 kilometers, and it is about 2 kilometers at its widest. Protruding over 20 meters above the desiccated muds in the northern part of the playa is a weathered knob of quartz monzonite, a feature aptly known as the "Grandstand." This paleo- island shows evidence of wave-cut erosion in the form of an overhang, approximately 10 meters above the playa muds on its south-facing side. Two dolomite knobs protruding from the playa surface to the east of the Grandstand also show signs of beveling, probably carved during a period of high-standing water during the Pleistocene. These sheared-off surfaces lie about 2 meters above the lake bed floor. High-standing ter-

race deposits may exist surrounding the Racetrack, but they are very likely obscured or buried by prograding alluvium.

1.2 Overview of Regional Geologic History

The Racetrack Playa (Figure 1.3) is situated in a Holocene rift valley along the northern end of the Cottonwood Mountains of the Panamint Range within Death Valley National Park. The mountainsides surrounding the playa are the source of sediment to the bounding alluvial fans and the muds of the playa itself. A complex geologic history is recorded in the rocks and structural features in the surrounding landscape. Detailed descriptions of the regional stratigraphy and geologic history include reports and field



Figure 1.3: The Racetrack, as viewed from the west on Ubehebe Peak. Note the igneous island known as the “Grandstand” protruding from the flat playa surface, and the encroaching alluvial fan on the eastern margin.

guides by Hunt and Mabey (1966); Troxel (1974); Fiero (1975); and Hardy (1988). A detailed geologic map of the Ubehebe Peak Quadrangle (incorporating the Racetrack Valley) was prepared by McAllister (1956). Descriptions of the stratigraphy and geologic structures of the Cottonwood Mountains in Death Valley National Park were discussed in a dissertation by Snow (1990).

The evolution of the Death Valley landscape began in late Precambrian time with the development of a massive carbonate-dominated accretionary wedge accumulated on the edge of the North American craton. This accretionary wedge became the foundation for the Cordilleran Geosyncline, the name applied to the extensive orogenic region on the western edge of the North American continent. Throughout the greater Death Valley area thick sequences of dolomitized limestone and quartz sandstone accumulated in a north-to-south trending trough from the late Precambrian through the Cambrian. The stabilization of a passive margin on the western edge of North America is represented by the series of Paleozoic formations (Hunt, 1975). Tectonic episodes affected both large portions of Cordilleran deposits during Devonian time (the Antler Orogeny) and the foreland region (early Rocky Mountain uplifts), however, the area around Death Valley was not significantly influenced by these events. Sediments accumulated when shallow seas flooded onto the western continental margin. Appendix A has a summary of Paleozoic rock formations exposed in the Panamint Range. A stratigraphic column of these deposits may be found in Figure 1.4.

The breakup of Pangaea beginning in the late Permian period changed the western boundary of North America from a passive to an active margin. The continental shelf, originally subject to the deposition of carbonate and fine quartz sands, changed to a region

Regional Stratigraphy of the Panamint Mountains Area Death Valley, California

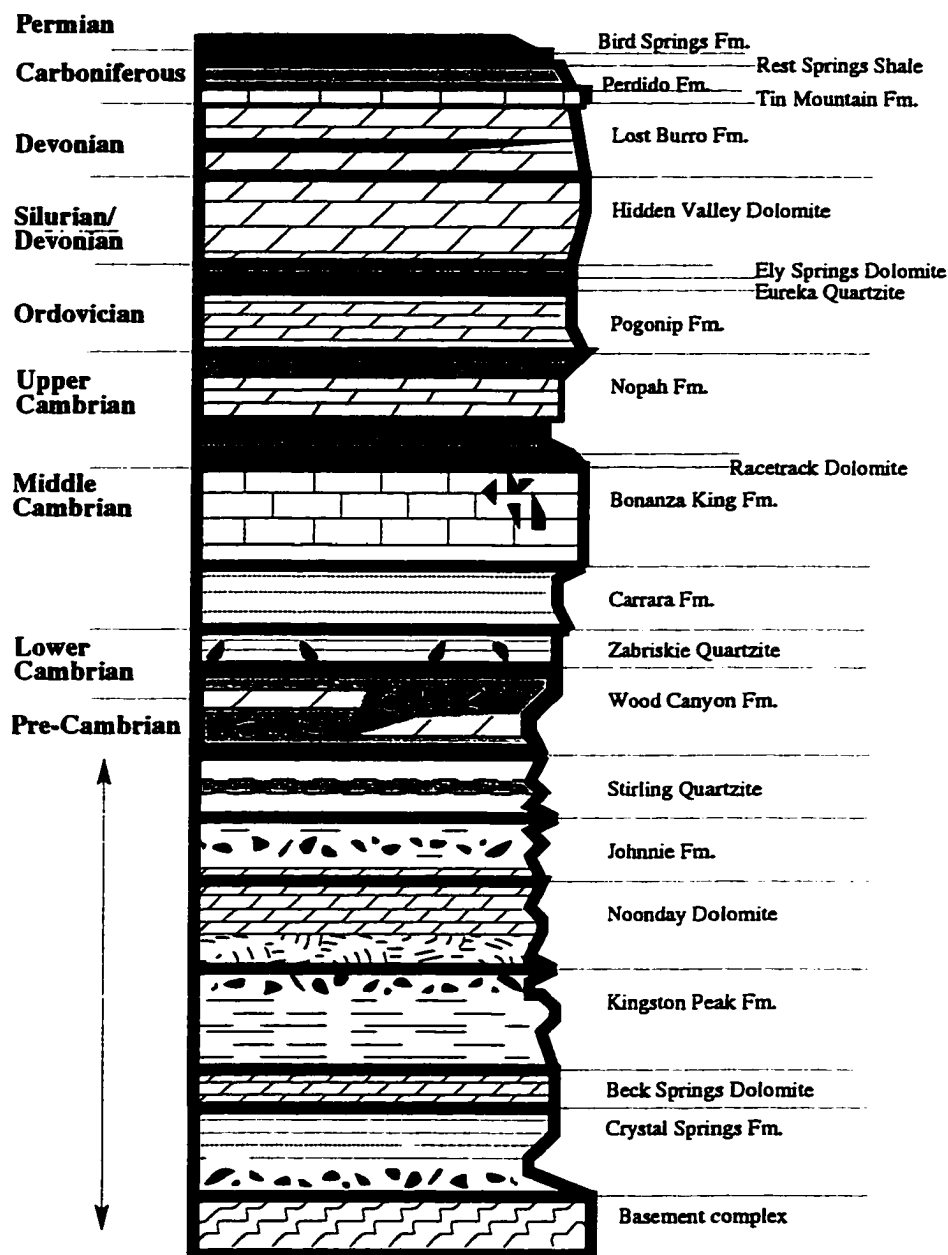


Figure 1.4: Precambrian and Paleozoic stratigraphy of the Racetrack Basin area. Descriptions of these formations appear in Appendix A. (After McAllister, 1956)

of active uplift and erosion, and eventually orogenesis and volcanism. The compressional forces associated with the evolution of convergent plate boundaries along the western continental margin resulted in the development of massive thrust sheets throughout the Cordilleran Geosyncline.

Large thrust faults and complex fold structures are apparent along the eastern side of Racetrack Valley. McAllister (1956) mapped a series of imbricate thrust sheets in the rough mountainous terrain on the northeast and southeast sides of the Racetrack Playa. Devonian and younger Paleozoic rocks have been thrust eastward over older Cambrian and Ordovician rocks. An outcrop on the south side of the playa consists of Late Cambrian dolomite which McAllister named the Racetrack Dolomite.

In the Cottonwood Mountains around the Racetrack Valley, complex fault structures associated with thrusting-style tectonism during the Nevadan Orogeny were already present prior to the emplacement of the Cretaceous age Hunter Mountain Monzonite. The Hunter Mountain Monzonite might more aptly be referred to as the "Hunter Mountain Intrusive Series" because it actually consists of a series of undifferentiated large and small plutonic intrusions throughout the Panamint Range, and it varies in composition from diorite to monzonite and granite. The composition of the Hunter Mountain intrusive rocks in the Racetrack Valley include monzonite displaying large phenocrysts of gray- to pink-zoned plagioclase. The plagioclase-bearing phenocrysts are exceptionally large and well defined on the Grandstand and on the eastern flank of Ubehebe Peak. On the mountain flanks to the east of the Racetrack Playa the igneous rock is more granitic in composition and displays finer crystalline development.

Around the margins of the intrusions are a number of skarn deposits where igneous

fluids have reacted with the surrounding dolomite. The skarns display an assortment of unusual minerals including the copper minerals chrysolite, cuprite, malachite, turquoise, and chalcopryrite. Ultraviolet fluorescence suggests a trace of zinc minerals and of the tungsten ore scheelite in some exposures. Economic mineral deposits were mined throughout the Racetrack Valley vicinity prior to the establishment of the national park. The abandoned mines, such as the Lost Burro Mine on the hilltop east of the Racetrack Playa and the Lippencott Mine to the south were quite large operations, yielding lucrative profits for short periods when prices for ore were high during the World Wars.

Volcanism and tectonism continued throughout the region from Cretaceous to the present, however the mode of tectonic deformation changed. At the beginning of the Tertiary an extensive subduction zone existed along the coast of western North America. During the Miocene, the North American continent overrode a spreading center in the Pacific basin. This caused a major change in plate geometry in the region encompassing California.

The Juan de Fuca plate, a remnant of a larger crustal fragment, vanished beneath western North America. Instead of a subduction complex, the geometry of the plates became a right-lateral transform boundary perhaps best represented by the modern San Andreas Fault (Winterer, Atwater and Decker, 1989). In addition, the spreading center that vanished beneath the North American Plate is still active; it may be responsible for the extensional tectonics currently in progress throughout the Great Basin (Stanley, 1989).

Extensional tectonic processes are responsible for the modern geography of Death Valley, specifically causing east-to-west extension with an element of right-lateral shear. The high relief in the Death Valley area reflects both the crustal thickening in early Ter-

tiary and crustal extension during late Tertiary to the present. The mountain ranges in the Death Valley region are slowly migrating southward as large massifs that are split and broken by extensive local faulting. Major faults border the mountain fronts with the largest, most active faults marking the east-facing slopes. Rotational movement (uplift on the western flank and corresponding sinking to the east) is apparent on the Panamint Range, the Funeral Range, and the Grapevine Mountains. The active faults responsible for the major uplifts and intervening basins are probably controlled by the location of older faults related to Mesozoic thrusting, or even to older Precambrian and middle Paleozoic deformational events (Snow, 1990).

The north-south striking Racetrack Valley is a graben, oriented tangentially to the larger structural southeast-to-northwest trend of Death and Panamint valleys. Saline Valley to the west maintains a southeast-to-northwest trend on its western side yet has a finger-like graben on its northern end that parallels the Racetrack Valley. This north-to-south graben is between the Saline Range on the west and Dry Mountain Peak on the east. The existence of this unnamed graben and the Racetrack Valley demonstrates that the Panamint Range is being extended by shear forces perpendicular to the greater east-to-west spreading of the bounding Great Basin province. The Racetrack Valley is covered by Holocene alluvium, but Pleistocene and older late Tertiary sediments may be buried by the surficial deposits.

1.3 Quaternary Surface Processes in Racetrack Valley

Recent erosional forces have shaped the Basin and Range province into the existing landscapes of the desert southwest. In arid regions such as this, wind and running

water (following infrequent but significant storm events) act as the predominant agents of erosion. Wind sculpts bedrock and accumulating sediment by the processes of abrasion and deflation. The abrasive action of windblown sand is evident throughout the area in the abundance of ventifacts (Laity, 1996; Figures 1.5 and 1.6) and pervasiveness of polished rock surfaces downwind of sand sources. In Death Valley fine examples of natural etching may be seen along the south side of Hanaupah Canyon fan, on a bench at the mouth of Artist's Drive fault block and at Salt Creek Hills (Hunt, 1975). Old mine debris, including bottles and other glass refuse, usually appears frosted from the relentless bombardment by sand. The sandblasting action of wind abrasion against exposed rock surfaces is limited to the basal meter or two of a rock mass that rises above a flat plain (Strahler and Strahler, 1997). Indeed, utility poles in Grapevine Canyon and other Death Valley localities are encased in protective metal sheathing to a height of about one meter to limit the abrasive action of windblown sand.

The effects of deflation are witnessed in the expanses of desert pavement surfaces common to the Basin and Range. Selective erosional removal of finer fractions of a sand-clay-gravel mantle leaves the coarsest materials behind as a surface armor protecting the undisturbed mixed materials below (Norris and Webb, 1990). Desert pavement forms a near-continuous surface layer in many of Death Valley's basins.

Other aeolian desert features such as dune fields are present in the Death Valley region, but like most basin and range dune systems, they are typically localized sand accumulations. From the Sierra Nevada eastward, the topographic basins of Owens, Panamint, Saline, Eureka and Death valleys each contain isolated dune fields. While the land area covered by dune fields cannot rival extensive "sand seas" of other deserts, the vertical

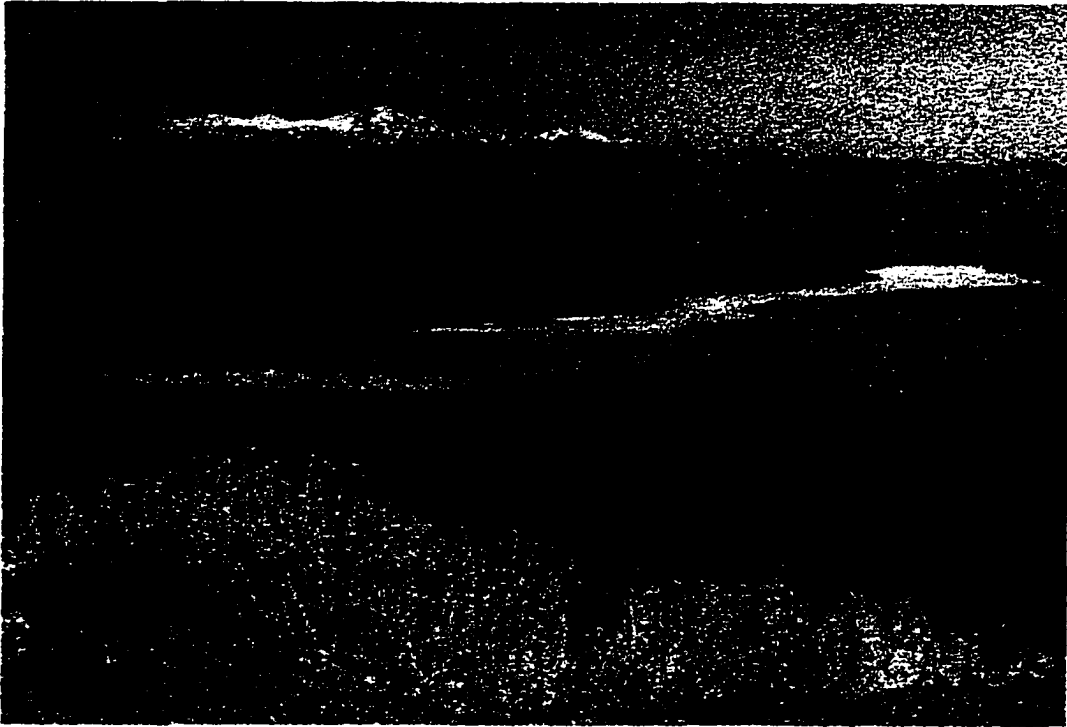


Figure 1.5: The north-south striking Panamint Valley is typical of Basin and Range landscapes. This view, from the northwest, shows North Panamint Playa and an extensive dunefield at the northern (downwind) end of the basin.



Figure 1.6: This *dreikanter* is typical of ventifacts found in the Mojave. This one was photographed near the downwind end of North Panamint Valley. (Field notebook for scale.)

extent of sand accumulations is noteworthy. Eureka Dunes, for example, rising 210 meters above the basin floor are the highest dunes in North America (Norris and Webb, 1990).

While the Racetrack Valley is fairly typical of landscapes in the region, it is unique in its expression of aeolian dynamics. With the exception of one climbing dune to the northwest, the Racetrack Basin is devoid of sand. Source materials for quartz grains are clearly present in the surrounding mountains, but do not accumulate in the area. In fact, the orientation of the Racetrack Valley's only sand ramp suggests that it serves as a source for the Saline Valley dune field, as grains are lifted over the top of the dividing ridge (Figure 1.7).

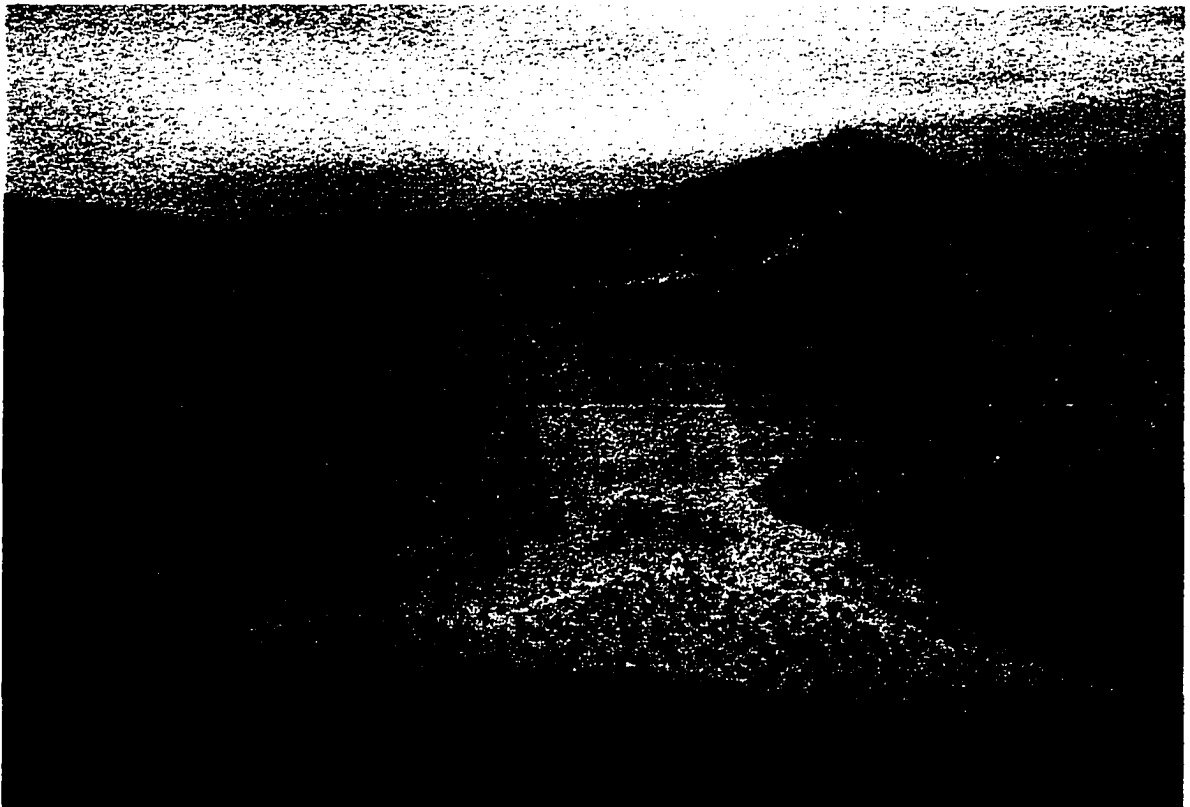


Figure 1.7: Unlike most other valleys in the Mojave Desert, this sand ramp is the only accumulation of sand in the Racetrack Basin. Its morphology and location suggest that local winds may be carrying sand grains through and out of the basin, to be deposited in Saline Valley to the northwest.

1.4 Sliding Rocks of the Racetrack Playa

While the Racetrack Basin displays physical evidence of common and expected aeolian processes, it also exhibits a somewhat unique phenomenon. Resting on its flat dry lakebed are pebble- to boulder-sized rocks, with masses estimated at up to 320 kilograms (Sharp and Carey, 1976). This in itself could be explained by simple mass wasting processes, yet the position of the rocks, often hundreds of meters from a source area, and the presence of furrows in the clay playa surface leading toward the rocks suggests that the rocks are moving by traction (see Figure 1.8).

Trails created by the rocks vary in length and direction. Some trails show gradual (curving) or abrupt (angular) changes in direction; most trails indicate a general south/southwest to north/northeast motion (Kirk, 1952; Sharp and Carey, 1976). Distances traveled of as much as 3.2 kilometers are inferred by the presence of distinctive lithologies far from possible areas of origin. Many rocks appear to break off dolomite cliffs at the south end of the playa, and are ultimately "deposited" where the playa meets an alluvial fan, about 2 kilometers to the north (Sharp and Carey, 1976; Messina, Stoffer and Clarke, 1997). Some trails are parallel to others that are in close proximity and generally strike from south to north, consistent with prevailing wind patterns, thereby suggesting wind as the motive force.

The nature of the trails recorded by inferred rock movement indicates that motion occurs only when the playa surface is wet, because smooth, rounded levees form and are preserved as "fossil wakes."

All sliding rock traces are ephemeral: the smallest ones may not survive a subsequent rainfall, while others produced by the most massive boulders may last no longer

than about seven years (Sharp and Carey, 1976). Hence, previous monitoring studies and limited-area maps generated may no longer be valid. Movement appears to be episodic and linked to the occurrence of storms (Sharp and Carey, 1976; Reid et al., 1995). Major "rock slides" are punctuated by stable periods, coinciding with dry conditions on the playa.

Despite years of interest and intermittent research investigations, no one has ever witnessed the rocks in motion. The mechanisms for these unusual events have been hypothesized and in some cases tested, but never proven.

This research project evolved from a natural curiosity about this exceptional aeolian process. It seemed essential to observe the scarred surface in plan view, and to ana-

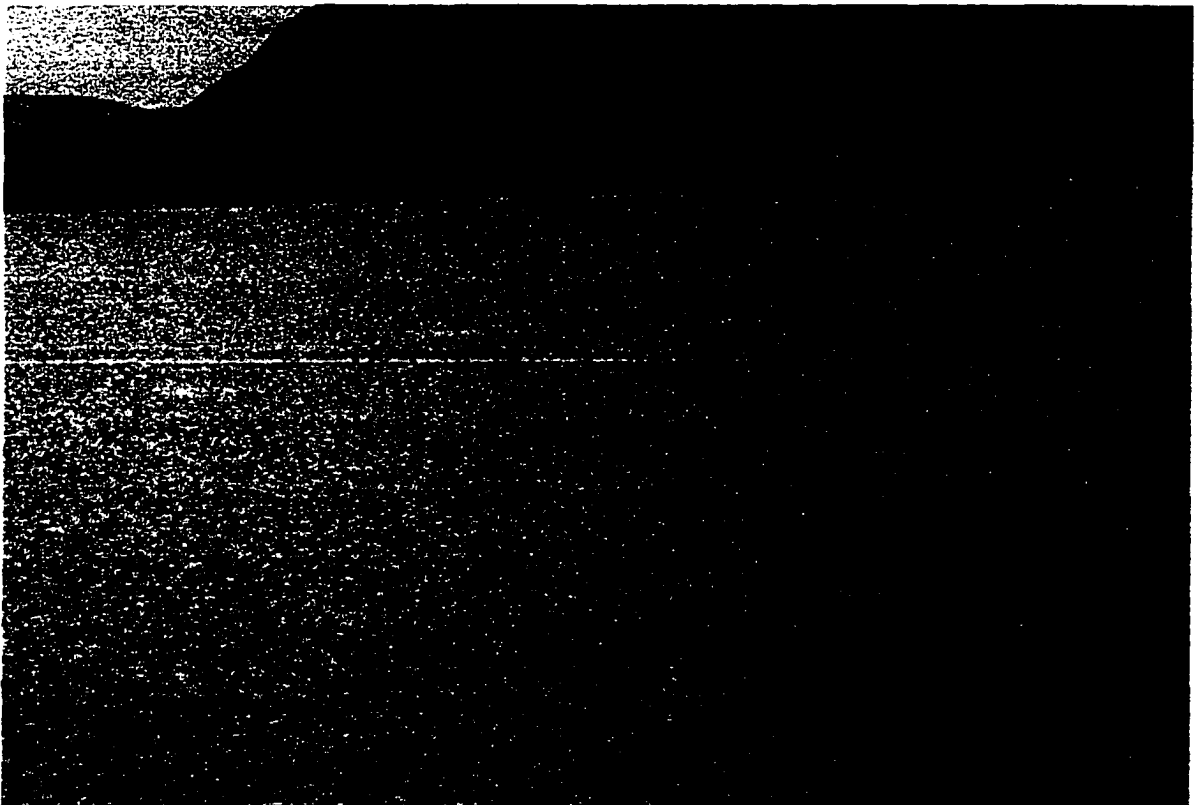


Figure 1.8: A typical sliding rock trail showing a general northeast heading.

lyze the spatial patterns inscribed by the rocks, particularly in the context of surrounding landforms. Despite the publication of several papers about this oddity, no complete maps of the Racetrack's trails were in existence. Compilation of the first detailed map of the furrows was paramount to a better understanding of the unexplained process responsible for the inferred rock motion. Several investigations described in the literature provided useful background information for the first complete survey mission and subsequent analysis of the Racetrack Playa's sliding rocks.

Chapter 2

Previous Investigations

While casual and scientific studies of the sliding rocks of Racetrack Playa span the twentieth century, it is not known when the features were first discovered. There is ample evidence of early habitation in the area by paleo cultures, such as the presence of chert tools and other artifacts (Hunt, 1975). An ancient trail parallels the boundary of the Racetrack, perhaps indicating periods in the past when the basin was more frequently filled with water. However, there is no record of the sliding rock phenomenon from prehistoric times.

The earliest account was documented by Stanley (1955), who described a 1915 visit to the Racetrack by Joseph Crook, a prospector from Fallon, Nevada. Crook brought his wife to the site, and showed her the stone tracks; she could not believe that the larger rocks could move naturally. She marked the position of one of the boulders, which eventually moved away.

The disbelief felt by Mrs. Crook is fairly universal among visitors to the playa, yet few researchers have attempted to follow through on their interest.

2.1 McAllister and Agnew, 1948

The first published account of Racetrack Playa's unusual surface processes was an abstract in the *Geological Society of America's Bulletin* (McAllister and Agnew, 1948).

McAllister had encountered the sliding rocks while mapping the geology of the Ubehebe Peak quadrangle for the U.S. Geological Survey (McAllister, 1956). The report contained only general descriptions as no precise measurements of the furrows had been taken. The authors speculated that “scrapers were propelled over the muddy surface of the playa, initially from the rim, by strong gusts of wind blowing consecutively from different directions, such as erratic whirlwinds that commonly produce dust-devils” (McAllister and Agnew, 1948).

2.2 Kirk, 1952

The next report was compiled by Louis T. Kirk, whose two years of unofficial studies (i.e., non-sanctioned National Park Service field work) were comprehensively recorded in the *Journal of Sedimentary Petrology* (Kirk, 1952). As a Death Valley ranger, Kirk was motivated by his personal interest in the phenomenon, and he sought to collect accurate measurements and representative photographs to capture and preserve the rare features. Concerned with increased visitation to the park, he noted that some human-caused disturbances had already occurred. Kirk made casual observations for years, but concentrated the bulk of his measurements during twenty hours of intense field work conducted over a period of just three days.

Activities included photographing typical trails; weighing a sampling of twelve rocks with spring scales; measuring trail lengths with a surveyor's chain; determining trail depth and width with steel tape; and sighting trail headings using a Brunton compass. The dimensions, general shape and orientation of the twelve rocks studied were meticulously detailed in the report. Kirk also noted three sediment-mound features which, although

irregularly shaped, were measured with steel tape and described according to orientation.

Although the physical characteristics of sliding rocks, trails and fine-grained sediment deposits were clearly described, their locations with respect to each other and to the playa outline were not. Kirk used his vehicle's odometer to find the minimum distance of each of his documented rocks to the playa perimeter, but his measurements lacked reference and direction (note that driving was fairly commonplace on the Racetrack until 1969). Locations were loosely described only in terms of quadrants (northeast, southeast, southwest, northwest), based upon imaginary and unreferenced north-south, east-west divisions.

Kirk found that the trails ranged from 34 to 786 feet (10 to 240 meters), and that the majority were straight or slightly curved with a general orientation running within 45 degrees of north from inception to terminus. He noted and photographed two trails that traced complete loops (see Figures 2.1 and 2.2). The images show a high degree of parallelism between convolutions in the trails, although it is not known exactly how close together these two traces rested. He notes that these two trails were both found in what he

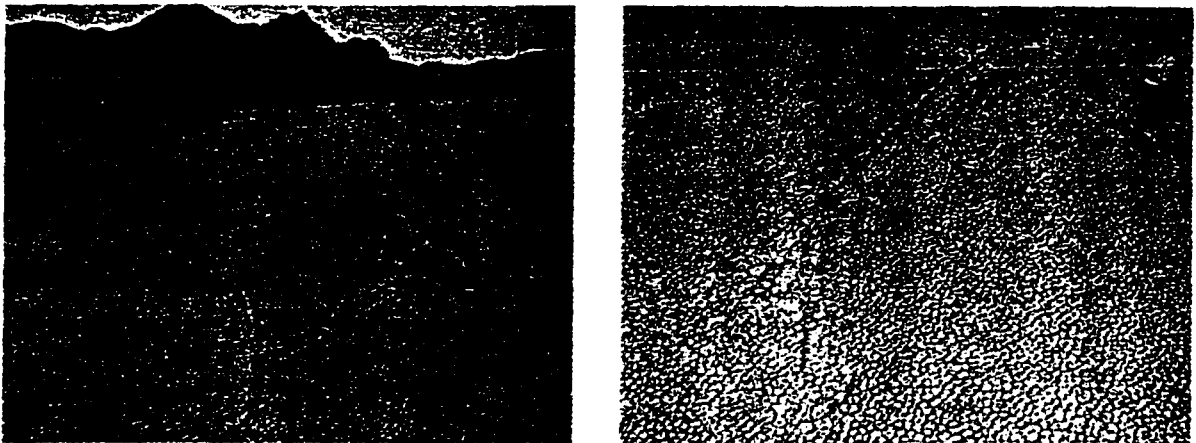


Figure 2.1 (left) and Figure 2.2 (right): show two trails as photographed by Louis Kirk (1952). The trails' locations were not noted, although it was recorded that the granite cobble that produced the trail in Figure 2.1 (Kirk's rock #9) was about 0.03 miles (45 meters) from the playa's perimeter, while the granite cobble causing the trace in Figure 2.2 (Kirk's rock #10) was 0.1 mile (160 meters) from the boundary.

deemed the “northeast quadrant” (boundaries were not specified). Both rocks were granitic; Kirk noted that their bottom surfaces were smooth, and he suggested that this erratic behavior could be explained by the physical character of the rocks themselves. Despite the high degree of congruence in the looped sections near the termini of the trails, the trail lengths varied considerably: Rock #9 (Figure 2.1) produced a trail that was 196 feet (60 meters) long; Rock #10’s (Figure 2.2) trail, at 786 feet (240 meters), was the longest one measured.

Of the twelve rocks described, Kirk included seven limestones, four granites and one quartz, ranging in weight from 1 to 603 pounds (mass equivalent: 0.5 to 274 kilograms). The largest rock was a rectangular carbonate boulder (Rock #6) with a 60 foot (18 meter) trail, heading towards the northwest (315°). Kirk noted that the largest rock neither produced the shortest trail (34 feet/10 meters, caused by one of the smaller rocks surveyed), nor did it move in the general heading of the majority of the sliders. Inferring that there was no clear relationship between rock volume and trail character, he paid close attention to rock shapes and orientations with respect to the trails they created. A summary of his collected data appears in Appendix B.

Kirk’s detailed field notes are commendable. His comment, “in general the rocks were oriented with the corner of their most streamlined appearing sides facing the trails” (Kirk, 1952) implies a rotation, possibly by wind, into this configuration. However, most of the rocks he sampled were described as “irregular” or “rectangular” hence the term “streamlined” seems somewhat contradictory. Having neither photographed each rock, nor referenced them to the trails they produced makes it difficult to decipher Kirk’s conclusion linking rock shape and trail orientation. Since only twelve rocks were described

(the reasons for selecting this subset were not offered), generalizations based on such a small sample are useful but not necessarily indicative of large-scale patterns.

While his paper focuses on field observations, Kirk speculated on possible causes for the phenomenon. He cites that a large number of hypotheses had been suggested by the time of his study (i.e., anthropogenic activity, including the use of the playa as a landing strip for a miner's airplane; magnetic anomalies; seismicity), but that the most logical causative agent was wind. Kirk described an experience during a four-hour period when the wind blew across the playa alternately from the east, west and south, at approximately 30 to 40 miles per hour (14 to 18 meters per second), which he regarded as a conservative estimate. Kirk noted that while it had been widely accepted that wind was responsible for the deflation of mud curls and movement of small stones, it seemed more plausible that the same mechanism was responsible for the movement of larger rocks than to suggest that another agent caused the more dramatic boulder-slides. As a patrolling ranger, he pointed out that summer cloudbursts or winter storms may provide sufficient precipitation to adequately flood the playa surface, although the only official weather data collected in Death Valley, nearly 4000 feet (1200 meters) lower in altitude, perhaps erroneously suggest that such events may not occur. Hence he concluded that natural processes that take place when a very special set of conditions are met can explain the incidence of sliding rocks on the Racetrack. His closing remark, "it is hoped that further investigation by other observers will provide a definitive answer" was heeded, resulting in the next published report only one year later (see section 2.4, page 24).

2.3 Clements, 1952

In the same issue of the *Journal of Sedimentary Petrology* as Kirk's landmark study was a published account of similar features on a nearby playa by Thomas Clements. Somewhat skeptical about the evidence and hypothesis suggested by McAllister and Agnew (1948), Clements visited the Racetrack in the spring of 1950 to view the sliding rocks for himself. After casual observation of the furrows, Clements agreed with the earlier paper's speculation that wind was responsible for the occurrence of sliding rock trails. While other methods had been suggested by then (Clements relates the possibilities of ice; tilting of the playa; water currents; and vibrations as possible moving agents), the occurrence of high winds after a saturation event seemed to be the most logical explanation. Yet Clements noted that if this were the case, then physical conditions similar to those on the Racetrack must occur elsewhere, and sliding rock phenomena should have been observable on other dry lakes. A literature review revealed no published reports of any such analogs, so Clements conducted a field survey of nearby playas in connection with a desert research project sponsored by the U.S. Army.

Just outside the northern extent of what was then Death Valley National Monument is Little Bonnie Claire, a dry lake of similar geographic setting, altitude and physical character to the Racetrack (see Figure 2.3). Clements visited the playa in January 1952 after a rainstorm. He reported that as the sun set, the low illumination angle highlighted the barely perceptible relief of three shallow trails. Measuring 20, 14 and 2 feet in length (6, 4 and 0.6 meters, respectively), Clements noted that the intermediate furrow was caused by the movement a small basalt cobble that still remained at its terminus.

He returned in March 1952 during a wind and rain storm, camping out at the

playa's north end. Clements described this twenty-four hour event as one in which winds frequently gusted to 40 miles per hour (18 meters per second) from variable directions, although most winds were northerly. On the day after the storm the playa was covered with 1 centimeter of water: "The clay surface was soft and extremely slippery, but beneath the topmost inch the material was quite firm so that a person walking on the playa sank down no more than an inch or two." Although difficult to "keep one's feet," Clements traversed the south and southeasterly portions of the playa where he noted numerous new trails. His descriptions are mostly qualitative, i.e., "some trails were straight, some were gently curved, a few had right-angle bends and a few were serpentinous." A few of the trails were measured, although the results of his measurements are only summarized in his

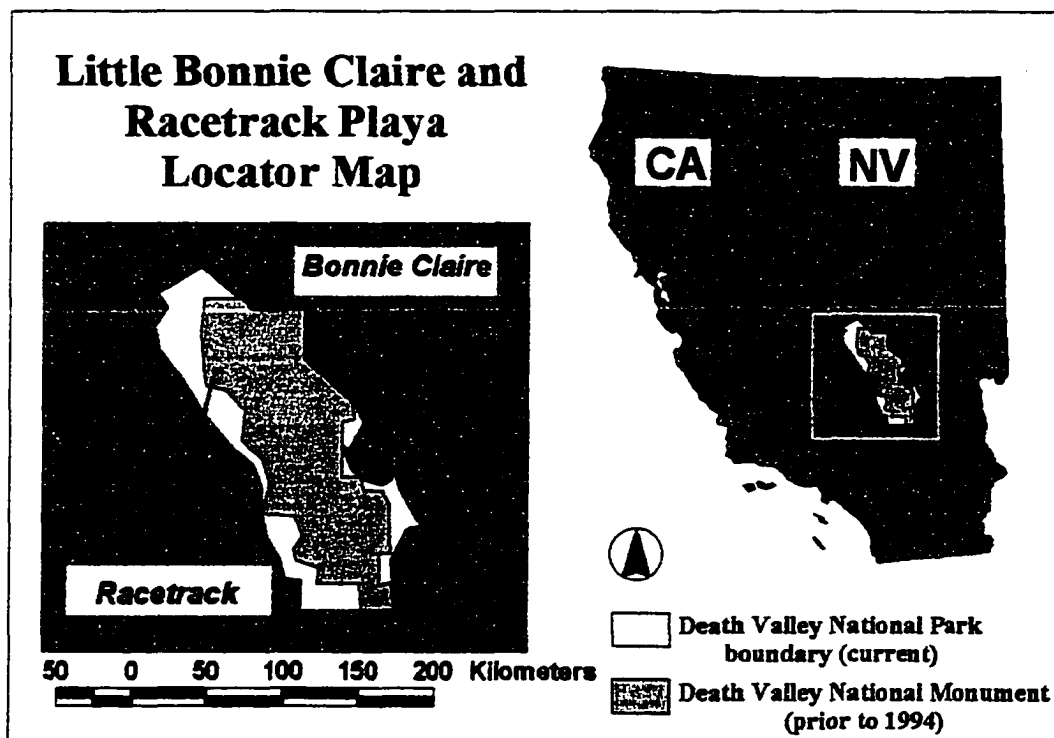


Figure 2.3: Locator map of Little Bonnie Claire and Racetrack playas.

paper; the longest trail witnessed was 138 feet (42 meters), while the shortest was only a few centimeters in length. All trails ended in cobble-sized basalt or scoria fragments, and headed generally from north to south.

Clements' observations led him to the conclusion that a combination of factors, including saturation of the uppermost clays and continual wind gusts, were all that was necessary to cause the rocks to slide. Snow covered the surrounding mountains during Clements' day at Bonnie Claire; the snow line was only slightly above the playa. Yet he doubted that accumulated water on the surface had frozen during the night. Although the ice floe theory had been suggested as a causative agent, Clements noted that the trails he observed showed little uniformity in direction and length. Furthermore, only some of the rocks moved; many had not. The lack of trail parallelism was attributed to "different [rock] sizes and local surface irregularities [compounded by] gusts from varying directions and varying competencies." As further evidence supporting the work of wind and water alone, Clements described several large boulders near the center of the playa; he contended that ice sheets would move all rocks in unison, regardless of size. Since ice-drag did not play a role in the transport of the cobble-sized rocks at the south end of the playa, it probably wasn't necessary to move the large boulders either, yet *something* propelled these large igneous blocks far from their source areas.

2.4 Shelton, 1953

John Shelton visited Racetrack Playa three times during April and May, 1952 to test whether wind could move stones as had been suggested by McAllister and Agnew (1948). He traveled to the remote location by light aircraft, landing directly on the playa

surface, and then used the plane as a source of artificial wind. He transported a supply of water, an anemometer, spring balances and laboratory-cut cubes (of unspecified material) ranging in base length from 1 - 8 centimeters. Flooding the surface with water, Shelton noted that "even 3 - 4 hours of soaking is not enough to produce a smooth slippery film of mud on the playa" (Shelton, 1953), and he estimated that it might take days or weeks to achieve a sufficiently low coefficient of friction to induce rock movement. Conceding that his technique did not mimic natural processes, he confined water to an area just over one square meter, allowed it to saturate the surface, and then used a trowel to produce a uniform veneer. The airplane's propellers generated wind speeds of no more than 42.2 m.p.h. (19 meters per second), but forces were great enough to push a triangular prism of limestone weighing 19 ounces (532 grams). The largest prepared cubes didn't move, but smaller ones tumbled. Shelton attributed this to a combination of the inherently greater pressure per unit area of the cubes' bottom surfaces, and to their low vertical profiles (friction retards wind speeds at close proximity to the playa floor). Further investigations took place "at a shallow, man-made water hole near the south end of the playa" (Shelton, 1953); introduced water was naturally contained, producing a thoroughly saturated material on which the 19 ounce prism and one other natural stone moved several times under the force of propeller wash. The researcher noted that movement was slow and hesitating, and that the mud surface was actively rippled by the air blast. Shelton surmised that natural conditions are probably more conducive to rock motion for two reasons. First, the artificially wetted surface was not as slippery because the uppermost playa crusts naturally contain the finest clays, and these had been stripped away at this depression. Second, the aircraft's propellers were capable of producing only unidirectional, steady winds of limited speed.

He noted the topographic configuration of the valley, and proposed that the terrain nurtures gusts of increased velocities, particularly from the southeast.

2.5 Stanley, 1955

Three years after Louis Kirk's invitation for further study of the Racetrack, George M. Stanley published a lengthy report in the *Geological Society of America Bulletin*. Stanley's first visit to the playa in December 1951 was no more than a cursory scan of the sliding rocks, but it prompted him to return for more intensive field analysis the following spring. A two and a half day visit in April 1952 resulted in the examination of several highly parallel tracks, which prompted an even more extensive mapping project a few months later. For eight days in August and September of 1952 Stanley conducted the first detailed mapping project of the Racetrack Playa's surface phenomena. With two more short excursions in November 1953 and April 1954 Stanley generated the first reasonably accurate plots of the playa's sliding rock trails.

Stanley established a series of base lines aligned by alidade on the playa surface and drove numbered tags into the dry mud alongside selected trails. Measurements from each tabbed point on a trail to two or more base line reference points were taken with steel surveyor's tape to the nearest 0.005 foot (0.175 millimeter). Base lines were interrelated by eight field measurements and later trigonometric computation to a resolution of about 0.05 feet (15 centimeters). Base lines and trail point locations were recreated on a plane table to a scale of 1 inch = 10 feet (1:120). Line features were sketched once the skeletal points were plotted, and Stanley admitted that there were some inaccuracies in his drawings due to the oblique vantage point of the field surveyor.

Concentrating field activities to the south end of the playa, Stanley mapped several highly parallel trails which varied in length between 200 and 300 feet (60 to 90 meters); when overlaid with each other the lines showed a high degree of congruence. Citing the similarities of these inscriptions, Stanley concluded that a cohesive ice sheet, measuring approximately 200 to 275 feet wide (60 to 85 meters) was responsible for rock movement. Deviations in trail length were explained as the result of an ice floe break-up. He studied trail orientation changes extensively, and described shifts in heading as the result of ice floe rotation. According to Stanley, large rocks at a distance from shore acted as obstacles; when a moving ice sheet of limited strength encountered one of these voluminous encumbrances the ice would crumple and pivot, causing changes in direction of over 10 degrees. Smaller trail “wiggles” were interpreted as the consequences of the ice sheet scraping against ice ramparts along a changing shore configuration.

A group of isolated trails more distant from the southern shore was mapped revealing analogously parallel pathways (see Figure 2.4). Unlike the majority of rocks, this group traveled from north to south. Figure 2.4 shows only one schematic of four presented by Stanley; it is representative of the survey’s level of detail, however only vague inset maps were included to help locate the general locations of the selected trails.

Upon analysis of these tracks, Stanley concluded that they were produced by a southward unit movement with counterclockwise rotation, and final divergence due to ice floe break-up. Further evidence, such as the lack of uniformity of rock size or shape in this isolated group, bolstered the ice-raft hypothesis, however Stanley did not include data on the physical nature of the rocks in his study.

Among his descriptions, Stanley observed that the longest trail was 872 feet (266

meters) although its location on the playa was not reported. He was perplexed that this extensive path was gouged by a 27-pound (12 kilogram) rounded dolomite whose long axis was transverse to the track for its entire length. The author questioned how wind could have accomplished this without causing the rock to tumble, and suggested that only ice could allow for the smooth sliding motion implied by the trail. Another example, also without geographic reference, was that of a rectangular dolomite block of 30 pounds (14 kilograms) with a trail that, for a substantial fraction of its total extent, crossed an area littered with small stones. An unnamed geologist cited in the paper presumed that this cobble could have slid on clay up to this debris puddle, then tumbled through it, resuming its tractive motion when encountering clay again on the other side. Stanley disagreed:

“It would be contrary to the laws of transport for wind to roll away this

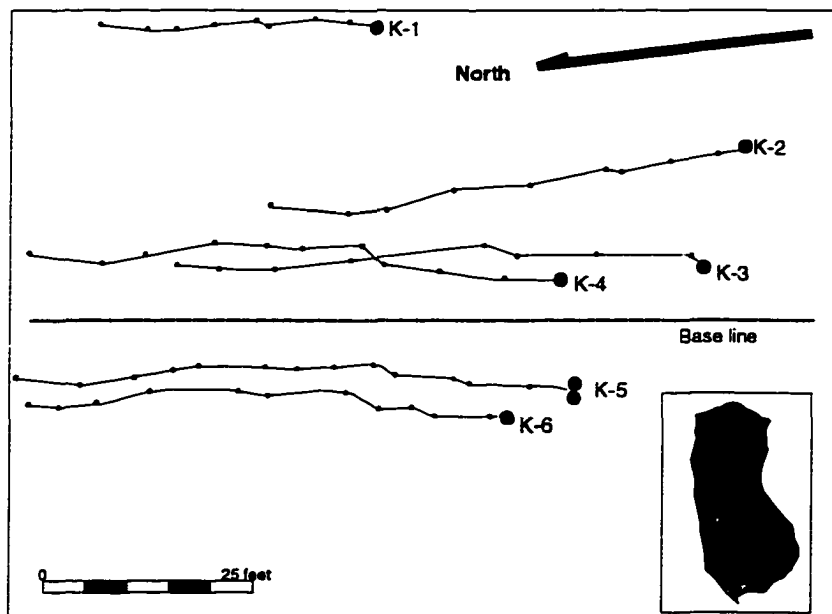


Figure 2.4: Six trails in the west-central part of the Racetrack Playa as mapped in 1952, showing the base line used for reference. Rocks moved generally from north to south and show similar motion (note that trail K-5 is headed by *two* rocks which may have moved in unison). Stanley concluded that all six rocks were embedded in an ice sheet that broke up, separating the rocks into two subsets: one including K-1, K-2 and K-3, and the other including K-4, K-5 and K-6. The second subset may have fractured further. Inset (lower right) shows the location of the enlarged map with respect to the Racetrack Playa's outline. (After Stanley, 1955.)

large rock and leave the hundreds of tiny stones that constitute the point traversed, even though most of the paved stones protect one another from wind. Also, to slide a rock over stones, unlubricated by wet clay and slightly upgrade, would require more force than wind could apply to it without ice as an intermediary.”

This statement and others neglect the cohesive nature of the playa muds when they become saturated. Stanley argued that light-weight materials, including twigs and burro droppings, could not be propelled by wind across the playa without tumbling, hence such objects would not leave characteristic scars. The fact that they did, he argued, offered further support for the ice-floe theory; Stanley envisioned protrusions in the ice sheet inscribing down into the soft muds as the entire frozen mass glided over the playa. However, the playa surface becomes both slick and sticky when saturated. Light objects, like the dolomite block, may resist tumbling and rolling because a single surface may be “glued” to the tacky surface, yet entire objects glide despite this fact; the forces may be substantial enough for propulsion, but not powerful enough to overcome surface adhesion to the gummy deposits below.

Stanley cited the work of Kirk (1952), but interpreted the observed mud mounds described by the earlier paper as the work of ice, possibly scraping the softened clays as a migrating ice tongue. Kirk measured an 84 foot (26 meter) swath that widened from 2.5 inches (6.3 centimeters) to 12 feet (3.7 meters); a feature with this morphology was originally interpreted to have been caused by spreading turbid water. Stanley explained this divergent pattern as the result of an ice floe that “pressed more widely on the mud as it overreached the bounds of a shallow supporting pool” (Stanley, 1955). Scalloped shorelines and ridges of large stones parallel to the encroaching alluvial fans at the playa boundary were interpreted as ice shove features. Stanley contended that rocks of “this size” (no

quantitative data were included) could not have been transported by waves in such a shallow lake. He specified several rocks, protruding about one foot (0.3 meter) above the playa floor evenly spaced along the western margin. The rocks were tilting to the south, implying that the prevailing winds that may have produced the ice rampart feature were emanating from the north. This conclusion is consistent with the southerly headings of trails mapped on the west side of the playa (see Figure 2.4.)

Bolstering the ice hypothesis, Stanley's paper included a narrative report of an incident that occurred on December 3, 1952 east of Reno, Nevada. The central transcontinental telephone line was suddenly and mysteriously disconnected, leaving many telephone customers without service. A repair team traced the source of the problem to a small lake in Carson Sink. Phone lines crossed Toulon Lake, a 775-hectare depression which was flooded that winter; at an elevation of 1188 meters above sea level, the water in the shallow lake had frozen. Repair personnel discovered that 20 telephone poles supporting over 1000 meters of cable had been knocked over into the lake. Some of the poles had been erected within corrugated metal reinforcements, but they too were uprooted. A sheet of ice 10 centimeters thick with a major axis length of 5 kilometers had formed on a half meter of water. Winds estimated at 15 meters per second caused the ice sheet to move, reportedly shearing off or uprooting the telephone poles, and transporting them and their mangled caissons about 100 meters from their original upright locations. Stanley contended that similar conditions may exist on the Racetrack, and analogous mechanisms may be responsible for the presence of sliding boulders.

When reviewing the work of previous researchers, Stanley responded to Clements who questioned why this phenomenon isn't more widespread. "A logical answer might be

that most other playas (of Mohave-Colorado Desert) are lower, and temperatures to develop sufficient ice would depend considerably on elevation” (Stanley, 1955).

A follow-up visit to the Racetrack in mid-April 1954 yielded many new, unmapped tracks. Among the fresh discoveries, Stanley noted a series of six irregular zig-zagging trails about one kilometer east of the Grandstand, a few tracks near the south end with a northeasterly trend, and most curiously, about 100 fresh southward tracks along the west side of the playa (Stanley, 1955). He noted that most of the trails, from a few centimeters to 6 meters long, were gouged by rocks but some were produced by twigs of sagebrush. A few more indications of recent activity were found southeast of the Grandstand, where rocks and burro dung produced southerly traces up to 23 meters long. Hence, it was presumed that conditions favorable to rock traction (whether by ice floe or wind alone) must have existed during the winter of 1953-1954.

2.6 Schumm, 1956

Noting the controversy between the two schools of thought, Stanley Schumm published a paper in the *Journal of Sedimentary Petrology* summarizing the relative merits of the ice floe and “wind only” theories. He cited the observations of Guilcher and Cailleux (1950) who described the presence of incongruously large pebbles (ranging in maximum dimension from 1 to 4 centimeters) forming discontinuous lenses 10 to 20 centimeters below the surface of the Veluwe Hills in the Netherlands. These sands constitute mounds up to 3 meters in height, and are believed to have been deposited during the Würm glacial epoch during the Pleistocene.

The deposition of the pebbles, as the result of aeolian transport, is difficult to rec-

oncile since the smaller particles constituting the Veluwe matrix material (sand, silt and clay) would have been deflated by forces capable of carrying pebbles. Guilcher and Cailleux (1950) suspected that the sand deposits may have been glazed by ice as wind carried pebbles away from adjacent stream channels. Pebbles may have skidded up these ice ramps until ultimately coming to rest in their current layers.

Schumm also reviewed the work of Grove and Sparks (1952) who conducted experiments to test the hypothesis of Guilcher and Cailleux. A pivotable slab of ice was placed in a wind tunnel capable of sustaining airflow at 75 kilometers per hour (21 meters per second). Beach pebbles ranging in mass from 4 to 56 grams (from 3 to 52 cubic centimeters in volume) were placed on the ice sheet positioned horizontally, and at increasing slopes. The researchers noted that the uppermost surface of ice melted during the course of the tests, thus further reducing friction. Their results showed that the largest sampled pebble (52 cubic centimeters) slid up a 5 degree slope when maximum wind speeds (75 kilometers per hour) were attained. Once in motion, the pebble continued moving up a slope 5 degrees steeper with wind speeds remaining constant. Results of their study, summarized in Table 2.1, show that pebbles of similar size to those found in the Netherlands could indeed be set into motion by wind, *uphill* on an icy surface, and could remain in motion on even steeper slopes by sustained wind speeds, or on constant grades by diminishing wind speeds.

Table 2.1: Wind velocity required to initiate movement of pebbles on various grades.
(After Schumm, 1956.)

Pebble	Mass (grams)	Volume (cubic cm)	Wind Speed in Kilometers per Hour		
			60	70	75
a	56	52	---	1°	5°
b	33	22	0.5°	5°	7.5°
c	24	14	1°	6°	9°
d	12	8	3°	16°	19°

Grove and Sparks (1952) noticed that the lightest pebbles rolled and tumbled while more massive ones slid. A graph of pebble weights versus experimental wind velocities required to initiate and maintain motion is shown in Figure 2.5. Extending these plots to include much larger rocks (as are present on the Racetrack) shows that wind speeds over 300 kilometers per hour are needed to overcome the inertia of a 1-kilogram cobble on a flat, icy surface (see Figure 2.6).

In response to the lower threshold speeds measured by Shelton, the author supposed that “the downward blast of propeller wash (may have been) a more effective propelling force than winds moving essentially parallel to the surface” (Schumm, 1956) as was the case in the wind tunnel. The graph shown in Figure 2.6 suggests that 0.5 kilogram rocks can be moved only by winds exceeding 140 kilometers per hour. Yet winds of this nature, according to Schumm, are uncommon, and rocks much more massive are typical on the Racetrack. It is for these reasons that he concluded that while wind alone may explain the uphill motion of the Netherlands’ pebbles, “some other agents must be intro-

duced to move the heavier rocks.”

This model assumes that the relationship between pebble weight and threshold wind speed is linear, and that the small sample size ($n=5$) and fairly limited size range used in this study are representative of much larger objects. The wind tunnel used directed air horizontally, which may not mimic natural conditions, particularly when considering the terrain surrounding the Racetrack playa. And yet another factor, pore pressure within a body of mud, was neglected in favor of substituting a uniform sheet of ice as the surface medium. The theoretical consideration of subsurface pressure was the topic of another paper by Sharp, published in 1960.

2.7 W.E. Sharp, 1960

Sharp’s paper derived the equations that may explain motion on a muddy surface taking into account internal fluid pressure. He defined the quantity λ which represents the

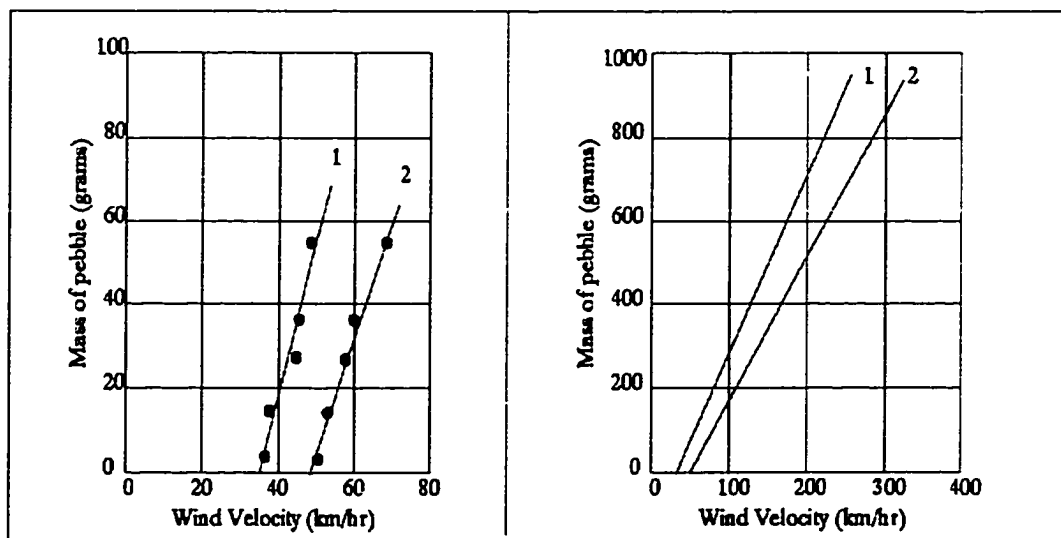


Figure 2.5 (left) shows the relationship between pebble mass and wind velocity needed to initiate movement on an icy surface (line 2), and that needed to maintain motion on an icy surface (line 1). **Figure 2.6** (right) shows an extension of the regression lines of Figure 2.5 to high wind velocities and larger sediments. Regression 1 shows wind speeds needed to maintain motion; regression 2 shows wind speeds required to initiate motion. (After Schumm, 1956.)

ratio of pore pressure to overburden pressure (i.e., the weight of the rock). This value can theoretically be equal to a maximum of 1.0, as in the case of suddenly placing any massive object on any water-saturated material (this is the principle behind the operation of an ordinary hydraulic jack). This pressure ratio decreases as water leaks from the pores under the object, hence values of 1.0 cannot be realistically maintained over time. However, the muds comprising the Racetrack surface are quite impermeable so pore-trapped fluids hardly migrate at all, maintaining a fairly high λ value.

Sharp conducted experiments at Harper Dry Lake in San Bernardino County, CA to determine realistic values for λ under natural conditions. He towed a conglomerate boulder (dimensions: 15 x 20 x 26 centimeters) in a mud-filled channel, and measured forces required to slide it with a spring balance. He noted that the surficial mud had to be no deeper than 3 centimeters since the rock tended to sink into thicker deposits, requiring forces two- or three- times greater to overcome resistance. His results yielded an experimental λ value of 0.64 for this rock sample.

The conclusions of Sharp's experiment were based on physical measurements and theoretical physics. A brief summary of the logic behind Sharp's progression follows. The frictional resistance of the rock to motion may be expressed by a variation of Coulomb's Law (Hubbert and Rubey, 1959):

$$\tau = \tau_o + (S - P) \tan \phi \quad \text{Eq. 2.1}$$

where τ = shearing stress necessary for movement; τ_o = cohesion to mud; S = normal stress caused by the weight of the rock; P = pore pressure in the mud; and ϕ = angle of internal friction.

Since:

$$\lambda = \frac{P}{S} \quad \text{Eq. 2.2}$$

then Coulomb's Law may be expressed as:

$$\tau = \tau_o + S(1 - \lambda) \tan \phi \quad \text{Eq. 2.3}$$

If τ_o approaches zero, then the equation reduces to:

$$\tau = S(1 - \lambda) \tan \phi \quad \text{Eq. 2.4}$$

Both sides are multiplied by the bottom (contact) area of the rock, resulting in:

$$F_1 = mg(1 - \lambda) \tan \phi \quad \text{Eq. 2.5}$$

where F_1 = force exerted by friction; m = mass of the rock; g = acceleration due to gravity.

The force exerted on the rock by wind is:

$$F_2 = \frac{1}{2} \rho_a V^2 C_D A_f \quad \text{Eq. 2.6}$$

where ρ_a = density of air; V = wind velocity; C_D = drag coefficient; A_f = frontal area of the object.

If the force of the wind equals or exceeds the force exerted by friction ($F_2 \geq F_1$), the conditions necessary for rock movement are met. Substituting into equations 2.5 and 2.6, this translates to:

$$\rho_a V^2 C_D A_f \geq 2mg(1 - \lambda) \tan \phi \quad \text{Eq. 2.7}$$

Solving for λ :

$$\lambda \geq 1 - \left(\frac{(\rho_a C_D)}{2g(1 - \lambda) \tan \phi} \right) \frac{V^2 A_f}{m} \quad \text{Eq. 2.8}$$

At standard temperature and pressure, $\rho_a = 0.001226$, $C_D = 1.05$ for a cube with a flat planar surface, $\tan \phi = 0.404$ for dry mud, and $g = 980 \text{ cm/sec}^2$. Substituting into Eq. 2.8:

$$\lambda \geq -1.63 \times 10^{-4} \left(\frac{A_f}{m} \right) V^2 \quad \text{Eq. 2.9}$$

Sharp plotted (A_f / m) values against λ for different wind velocities, and concluded that all relationships necessary to calculate requisite rock movement on the playa were derived. Masses and dimensions of the twelve rocks sampled by Kirk (see Appendix B) were converted to *cgs* units and substituted into Sharp's derived equations. Sharp concluded that wind speeds greater than or equal to 37 meters per second would be required to move the conglomerate specimen used in his experiment on a saturated playa.

Noting that the act of placing the sample boulder into the wet channel resulted in higher measured pore pressures than those assumed common in nature, Sharp specified that measured λ s for rocks decreased when they were placed on a dry surface subsequently saturated (i.e., values far less than 1.0 [$\lambda = 0.34$] resulted when the playa deposits were artificially flooded). He deduced that "even in the special case where the rock is placed on wet mud, reduction of the effective coefficient of friction of sufficient magnitude to explain the movement of the majority of skidding rocks could not be obtained."

Using actual playa deposits and calculated values of λ , the coefficient of sliding friction was estimated as ranging from 0.145 to 0.26. Theoretical wind speeds from 33 to

45 meters per second (75 to 100 miles per hour) were calculated as traction thresholds for a rock placed on an already-wet channel, and for a rock on an artificially flooded initially-dry playa, respectively. Still, Sharp concluded that “wind velocities required to move playa scrapers over surfaces of wet mud are higher than those commonly met in nature.”

2.8 Creutz, 1962

Another hypothesis totally discounted wind as a driving force. In 1962, E. Creutz argued that since “each of the rocks had its own well-determined direction of motion, and these directions are all different” wind could not be responsible for the phenomenon. He similarly dismissed the suggestion that seismic activity in the area contributed to the rocks’ movement, but proposed yet another possibility. Creutz stated that the rocks move downhill, and that the boulders respond merely to the force of gravity.

Having visited the playa, Creutz noted that many trails indicated movement away from the shore and towards the center of the dry lake. Yet some trails that he observed had acute changes in direction; in one case a rock appeared to have moved in opposite directions with a near-180° turn midway. Although this single observation may appear to contradict Creutz’s belief, he explains that “downhill” is a rather temporary and changeable direction, dependent on the water content in the playa muds. He contended that a significant component of the playa sediments is bentonite or similar swelling clay, and that after a rain storm the surface slowly rises.

Assuming that the Racetrack surface is perfectly level (contradicting the observations of Stanley [1955] and others) Creutz suggested that differential saturation of the playa muds would cause some sections to swell more than others, resulting in a distinct

gradient. This thixotropic behavior is a function of the amount of wetting, and on the depth of the clay layer. According to Creutz, nearshore clays absorb more water due to the proximity of an impermeable barrier underneath, and therefore tend to rise. The resulting bowl-shaped playa surface would promote rock movement away from the encroaching alluvial fans. The dilemma of the rock that reversed direction was justified by the author as follows: “with continued rainfall the swelling of the thicker mud near the center of the lake will be greater than that of the thinner layer near the shore.” Creutz believed that with continued flooding, the central deposits rise farther, and send the rocks back towards the now-lower shore.

Creutz described “two sink holes near the southern shore of the lake, about 200 feet from its edge.” No maps were included in his report, so the exact location of these features is vague. Creutz believes that these depressions indicate outlets for water, and that they are positioned at the lowest part of the playa. He reported that many of the rocks appeared to be moving in a direction leading to those craters, and that some tracks end in them. While this supports his “gravity only” theory, it does not explain the 180° bends in some trails.

Creutz tested the effects of saturation on different depths of swelling clays in the laboratory. Using dry bentonite (although the bentonite fraction of the Racetrack is not known), he added water to varying quantities of the material packed into graduated cylinders. He found that thin layers of bentonite expand and reach maximum volume more rapidly than thick layers of the clay. This occurs because water initially fills pore spaces, and only later penetrates the crystalline layers of the mineral (which is what causes the volumetric increases). Thin layers of clay have few pore spaces that are filled rapidly; surplus

water is free to assimilate into the sheet silicate in a short period of time. Longer infiltration periods are required to clog the pores of thicker clay deposits, so expansion is delayed. Another experiment showed a direct relationship between the amount of water added to bentonite and the resulting degree of swelling. Creutz concluded that “this experiment and analysis thus seem to verify the hypothesis that the swelling of mud as it absorbs moisture accounts for the rocks’ moving about the Racetrack” (Creutz, 1962).

2.9 Bradley, 1963

Harold Bradley’s first visit to the Racetrack was in April 1956 when, after several days in Death Valley, he was surprised to observe it as a lake-filled basin. Although Death Valley hadn’t received any precipitation during his stay, he remarked that the incidence of rain must be highly localized for there to have been a substantial accumulation on the playa. He explored the southern water-filled end of the Racetrack on foot, where there was as much as 4 inches (10 centimeters) of standing water; coating the sub-aqueous surface was “exceedingly slippery shallow mud on a firm base” (Bradley, 1963). The water did not seem to infiltrate the playa deposits too deeply, and Bradley was surprised when he dug a three-foot (one meter) deep hole near the water’s boundary to see that the clay was absolutely desiccated.

The ponding water was propelled by a strong southerly wind, and it formed tongues that moved uphill towards the north. The fan-like feature described by Kirk (1952) and interpreted by Stanley (1955) as the work of ice may in fact have been produced by a wind-driven migrating distributary as witnessed by Bradley. The researcher drove on the playa and found that his vehicle skidded across the progressing “fingers,”

regaining traction and coming to a halt only after reaching the dry hard-baked clay beyond. His experience led him to remark that “when wet for a half inch or less (the clay) forms an effective lubricant over which small bottomed stones might slide easily if pushed in some way.”

During his 1956 visit, Bradley observed several trails with no rocks present at either end. He surmised that blocks of ice, as proposed by Stanley (1955) may in fact have produced such features. However, the reports of Ranger Louis Kirk (1952) intimated that such scars were produced by rocks that had later been vandalized. In fact, Bradley described one trail with a decidedly rough appearance, as though the rock that produced it was dragged on the playa when it was dry. Another suspect trail had footprints alongside, suggesting that a rock had been dragged by people. Yet the vast majority of the trails appeared to be of natural origin; Bradley reviewed the most popular hypotheses in his paper.

He suggested that Creutz’s proposal that rocks are influenced by gravity alone needed further study, citing the possible role of differential swelling of clays as valid. Yet Bradley pointed out that Creutz limited his discussion to trails heading in towards or out from the center of the playa. Stanley’s (1955) detailed inventory documented many rock paths roughly parallel to the western shore; the thixotropic nature of clays could not be used to explain the existence of trails where slopes were not expected.

Bradley found merit with both the ice floe hypothesis suggested by Stanley (1955), and by the aeolian transport mechanism supported by McAllister and Agnew (1948). He pointed out that while unit motion of groups of stones was suggested by some of Stanley’s plots, the presence of large numbers of independent trails implied that ice was not required

for rocks to slide. In either case, the author believed that wind was ultimately “the motive power when surface conditions and wind happen to be precisely right” (Bradley, 1963).

2.10 Sharp and Carey, 1976

An extensive survey of the Racetrack’s sliding rock activity was conducted over a span of seven years by Robert P. Sharp and Dwight L. Carey. Visiting the playa on sixteen occasions from May 1968 until May 1975, the duo monitored the progress of thirty labeled rocks by fixing their positions with respect to steel stakes driven into the clay surface. When rocks moved from their original referenced positions, new stakes were buried alongside. Of the thirty rocks sampled, twenty eight moved on at least one occasion during this lengthy investigation.

This was the first such long-term approach used by a research team, and the information gleaned over time far surpassed that of any single previous study in quality and quantity. Although Sharp and Carey never actually witnessed any rocks in motion, having a baseline for comparison to previously-made measurements allowed them to infer periods of greatest activity. They found that events were episodic; greatest activity occurred during the winters of 1968-1969, 1972-1973, and 1973-1974 (Sharp and Carey, 1976). Still, some rocks moved in none of these events, while others moved in one, two or all three.

Rocks sampled were spatially distributed over the southern end of the playa (see Figure 2.7), and they represented the variation in lithology, shape and volume of specimens common to the Racetrack (see Appendix C). Rocks were marked, assigned letters and names, after one syenite specimen produced a “beautiful trail” between visits early in the study. Sharp and Carey named the rock that had produced this 64-meter track “Mary

Ann” after the wife of a friend. The tradition continued, and each rock in their survey was ultimately designated by a woman’s name.

The two men produced trail maps using Brunton compass headings and by pacing the rocks’ routes. The authors cited Donald W. Carney, a ranger at the time, who correlated rock movement episodes with contemporaneous meteorological events. For example, while visiting the playa on February 28, 1969, Carney noted several new trails; a significant winter storm took place on January 14 of that year, so he concluded that activity must have followed that rain. More precipitation fell on March 8 and, Carney noted during his next visit on March 17, the same rocks had moved again.

Rock movement was not limited to major events since a few stones (E, “Peggy”

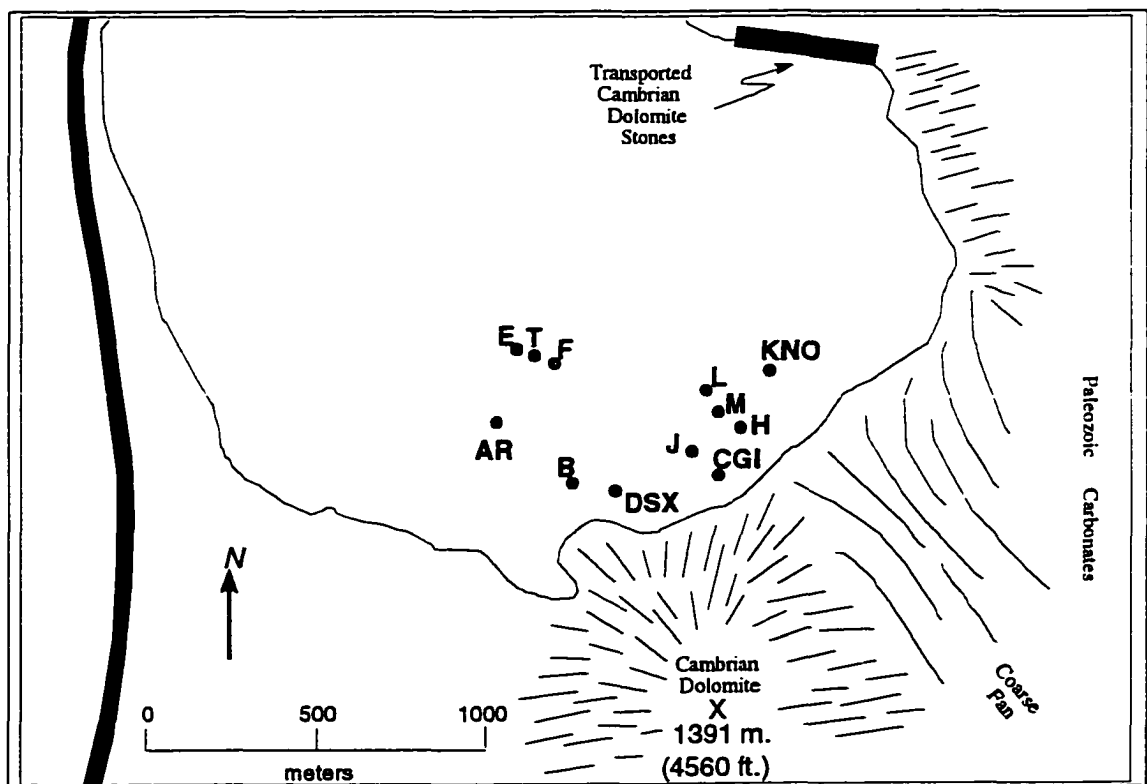


Figure 2.7: Approximate locations of labeled stones in Sharp & Carey’s study. Letters refer to individual stones, or the rock clusters described by Table C1, Appendix C (page 248). (After Sharp and Carey, 1976.)

and R, “Hortense”) made trails when no other rocks did during the winter of 1970-1971. The frequency and timing of his visits that fall helped Carney conclude that these isolated rock movements took place on or about December 2, 1971, three days after a heavy rain on November 29.

The longest single-event trail carved during the seven-year period was 201 meters, and the greatest cumulative movement was 262.3 meters; both distinctions are held by a small irregular cobble (H, “Nancy”). Appendix C details the extent of trails produced during the survey period.

The direction of movement was predominantly from southwest to northeast during this period, with each trail displaying its own share of deflection from net heading (see Figure 2.8). An aberration of as much as 63° was noted for one segment within an otherwise ordinary northeast-heading trail (R, “Hortense”). Sharp and Carey linked the relative straightness of furrows to the basal configuration of the rocks causing them. They contended that angular rocks produced the most regular paths, while smooth or rounded rocks tended to wander erratically.

Clusters of rocks in the groups labeled D, G and C showed significant departures from the general northeasterly trend, and members of the K, L, M, N and O groups experienced 90° clockwise deviation from the norm in 1972-1973, resulting in southeast-headings. Figure 2.7 shows the locations of these rocks closest to the playa boundary. Unusual deflections in these localities “possibly reflect a perturbation of the wind pattern by the south shore bedrock ridge” (Sharp and Carey, 1976).

Single stones were reported to have displayed contrary motion to that of nearby rocks during the same movement episode. For example, Sharp and Carey cited stone I

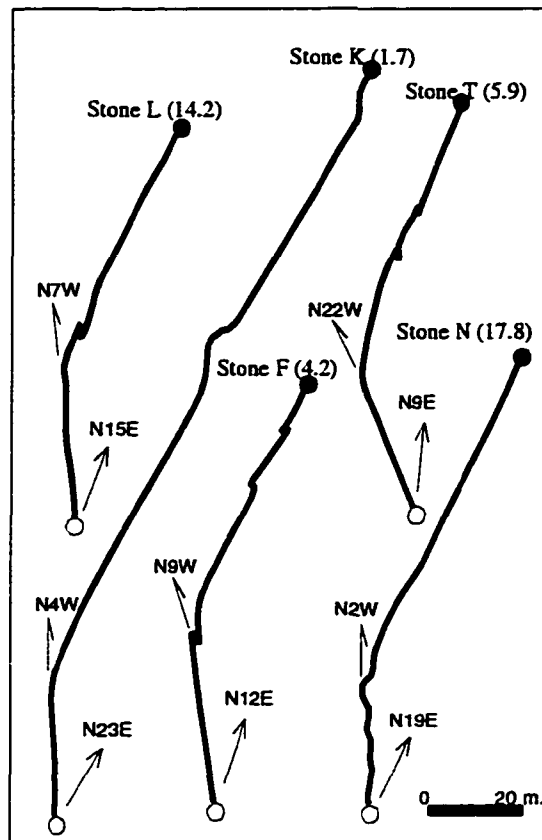


Figure 2.8: Plan of trails produced by rocks between January 14 and March 17, 1969. Masses of some rocks (in kilograms) appear in parentheses. Single barb arrow shows initial movement direction; double barb arrow shows net heading. Maximum separation between tracks is about 600 meters. Note the general northeasterly heading and individual variations within this trend. (After Sharp and Carey, 1976.)

(“Kristy”) which moved north for 50 meters, and then back towards the south-southwest an additional 55 meters, coming to rest only 20 meters from its original starting point. The event in which this erratic behavior took place was in 1973-1974 when 23 of the 30 monitored rocks moved in a northeasterly direction (see Appendix C).

The highly independent behavior of the thirty monitored rocks is inconsistent with the ice floe theory discussed by Stanley (1955), yet Sharp and Carey described evidence of freezing conditions on the playa. Striated swath marks across the mud cracks were interpreted as the results of ice sheets scraping against the playa surface, and the researchers

also noted that ice molds were preserved in the fine-grained sediments. Sharp and Carey designed an experiment to test the hypothesis that ice sheets play a role in rock movement.

Steel stakes were arranged in a 168 centimeter circle known as “the corral” (see Figure 2.9). Several rocks were placed into the space defined by the stakes, and their positions were monitored. On two occasions, a rock slid out of the corral, leaving the others behind, and creating a trail beyond the boundary defined by the stakes. Sharp and Carey noted that when stone XX moved in 1973-1974, another rock of similar character remained undisturbed. If ice sheets propelled rocks as a unit mass, this observation could not be explained. In fact, the stakes themselves would cause ice to fracture, implying that none of the rocks in the corral should have moved if ice provides the only vehicle for activity. Besides this set-up, natural concentrations of stones on the open playa floor exhibited nonuniform behavior, which suggested that ice is not a significant factor.

Based on the results of this monitoring arrangement, Sharp and Carey concluded

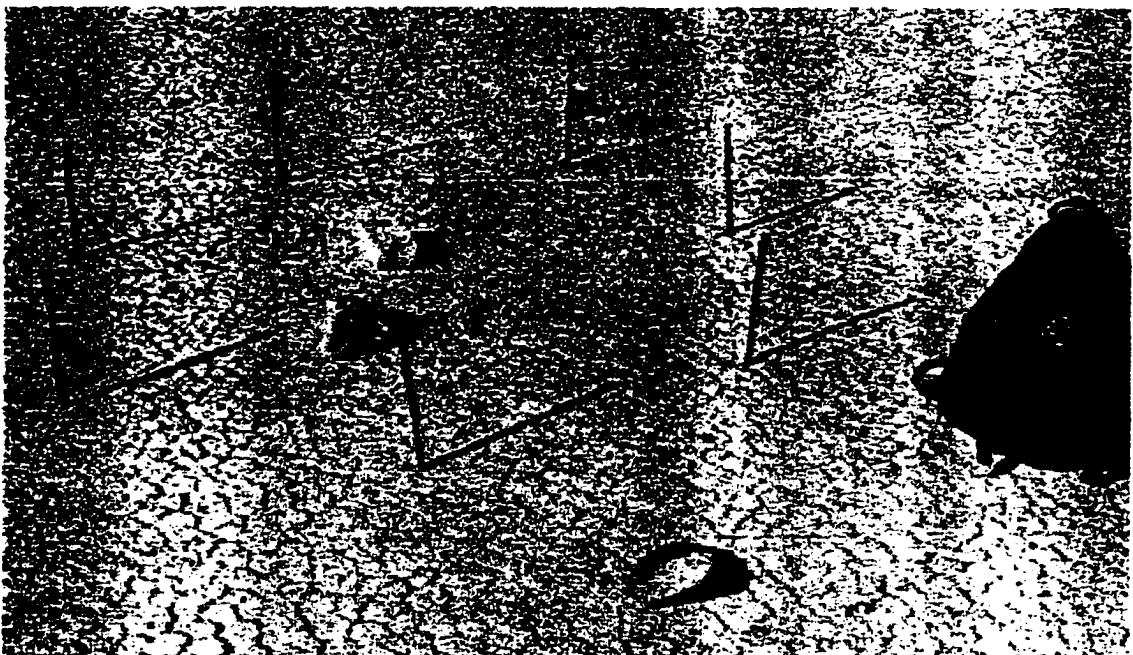


Figure 2.9: The “corral,” constructed by Sharp and Carey contained several rocks, only some of which slid out. (From Sharp and Carey, 1976.)

that “stones are individually skidded and rolled along a wetted surface of Racetrack Playa by wind, in spite of calculations (by W.E. Sharp, 1960) and comparisons (of Schumm, 1956) suggesting that this is unlikely because of the unreasonably high wind velocities seemingly required” (Sharp and Carey, 1976). The incidence of diverging, converging and crossing trail configurations (see Figure 2.10) inscribed during inferred solitary events implies that rocks are forced by wind alone when the physical nature of the playa surface meets a set of prescribed conditions. While Stanley suggested that non-parallel trails may result from ice floe break-up, Sharp and Carey recommended an alternative explanation. Were the playa saturated so that a thin slimy film formed on the surface collecting between

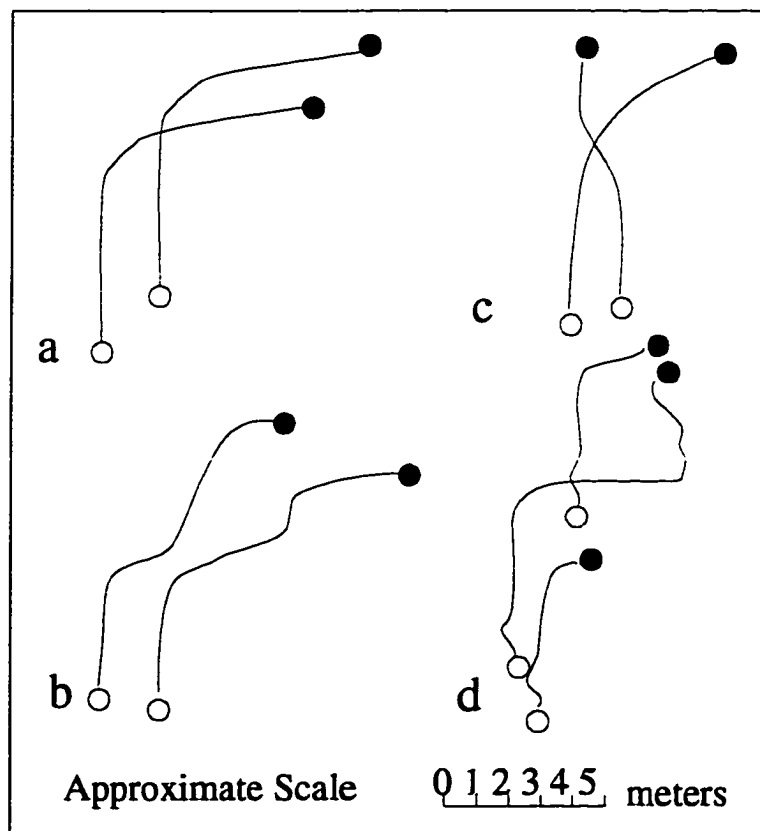


Figure 2.10: Diagrammatic sketches of field relationships of small stone contemporaneous tracks. Closed circles indicate the terminal positions of the rocks; open circles mark origins. (After Sharp and Carey, 1976.)

desiccation polygons, this fine clay veneer may provide an almost frictionless surface on which rocks can move under natural wind conditions. They added that rock movement takes place some time following flooding events, after the settling of the finest clays out of suspension. Sharp and Carey argued that earlier experiments conducted by Shelton (1953) did not allow for the formation of this fine clay film; since experimental conditions did not adequately imitate natural processes, Shelton's results may have over-estimated the force of wind necessary to move rocks. Furthermore, based on observations of trail morphology, Sharp and Carey estimated that rocks may slide at a speed approaching 1 meter per second during major rock moving episodes. This contrasts Shelton's observations of the "hesitating and slow" movement of his experimental cobble (Shelton, 1953), not to mention the almost imperceptibly sluggish progress predicted by Creutz (1962). Despite the convincing arguments offered by the valuable contributions of Sharp and Carey, the possibility that wind alone may cause this phenomenon continues to be debated.

2.11 Reid et al., 1995

A team of researchers headed by John B. Reid published the results of observations made during seven visits from 1987 to 1994. To test the previously proposed hypotheses, the group mapped widely spaced tracks into a precise coordinate system with an electronic theodolite. They also conducted direct measurements of forces required to slide a representative boulder on an artificially wetted surface. Their results provided strong evidence in favor of the formation of ice rafts as a precondition for rock movement.

Reid and a group his of students plotted "a large number of widely spaced tracks" following episodes of motion in the 1980s and early 1990s. Distances between the trails

surveyed was as great as 500 meters. Translating the trails to the same start point (0,0) they found a striking congruence between them despite wide distances separating them (see Figures 2.11 and 2.12).

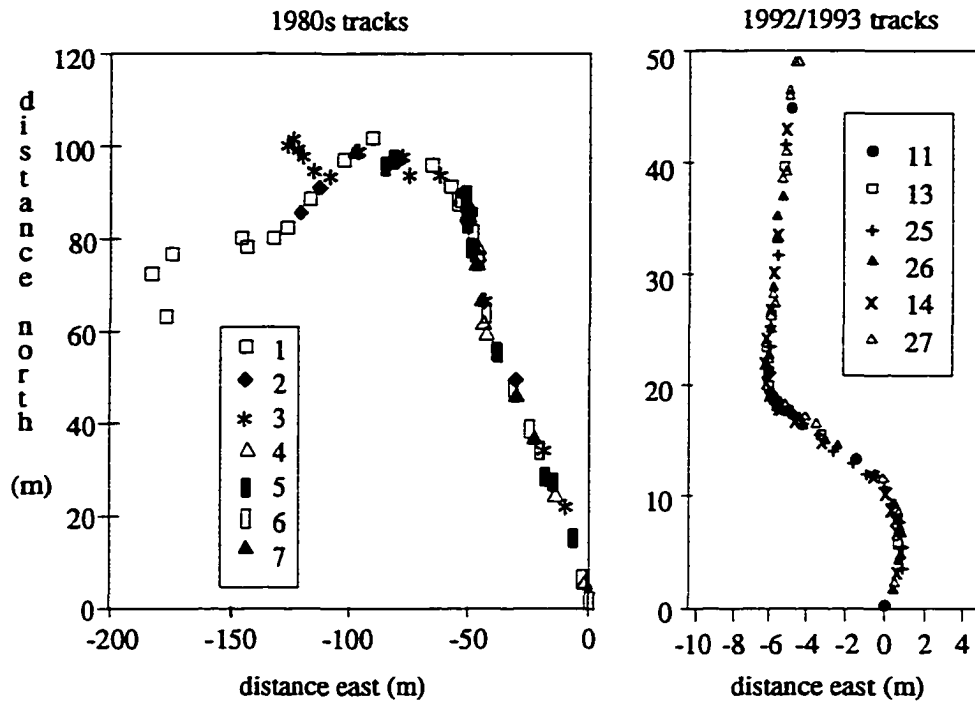


Figure 2.11 (left): Seven tracks mapped in the 1980s normalized to 0,0 show remarkable congruence initially, with later divergence. **Figure 2.12 (right):** shows six trails plotted after a 1992-1993 episode. Numbers and symbols in the insets of each graph represent rock identifiers. (After Reid, et al., 1995).

Initial parallelism was sometimes followed by ultimate divergence (Figure 2.11), and was explained by the researchers as the result of ice floe disintegration. The 1993 survey resulted in dramatic intertrack correlations between 23 mapped trails (Figures 2.13 and 2.14).

Reid et al. used the outstanding results of their surveys to bolster the idea that ice is an essential component of the rare playa processes. They addressed the results of Sharp and Carey's (1976) corral experiment which appeared to categorically oppose the ice sheet hypothesis. "With thin ice (~5-10 mm.), steel rods may have shredded ice that was capa-

ble of moving the small (~1 kg.) rock out of the enclosure” (Reid, et al., 1995).

Further substantiation was added when the results of a friction measurement yielded a surprisingly high value. The group surrounded a 12-kilogram angular dolomite fragment by wooden slabs, flooding the area with water. Two hours afterwards, the muds were saturated to a depth of 3 centimeters. Dislodging the rock required a force about equal to the rock’s weight (w), but motion was sustained by forces as low as $0.6 w$. Based on these spring balance measurements, it was estimated that the coefficient of kinetic friction (μ) for this rock on this artificially wet surface was 0.8. This value seems inordinately high, but was defended as a direct result of the irregular rock fabric of the specimen. To contrast, the coefficient of friction for bare feet on the flooded playa surface is estimated at 0.1 (Reid et al., 1995), which is about the same as that for ice on ice (Bacon, Cahill and Tombrello, 1996). These estimates suggest that the small percentage of smoother, more-rounded rocks move more frequently, yet none of the surveys found this to be true. Reid et

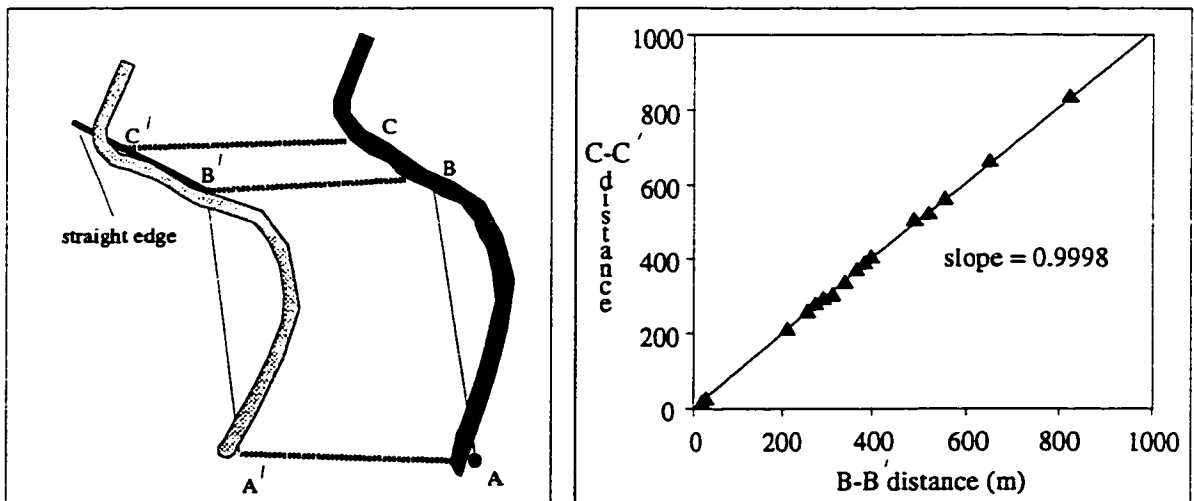


Figure 2.13 (left): A schematic representation of actual intertrack and intratrack distances. A six-meter straight edge was used to locate common tangent points, B and C, of gently curving tracks. **Figure 2.14 (right):** Comparison of intratrack distances for 23 trails in 1992-93 computed as shown in Figure 2.13. Trails were separated by up to 300 meters, and yet the absolute measured difference between B-B' and C-C' values is 6.4 ± 5.6 cm. Regression line shows a very high degree of correlation. (Reid, et al., 1995.)

al., used this revelation to promote the ice floe hypothesis as well.

It should be noted that this method of artificial saturation was questioned by Sharp and Carey twenty years before when reviewing the work of Shelton (1953). As with the earlier experiment, Reid et al. did not account for the formation of a thin film of the smallest clay fraction, which would expectedly settle out of standing water over time. The expediency of measurements made by Shelton (1953) and Reid et al. (1995) may be to blame for the unusually resistant surface conditions reported.

2.12 Bacon, Cahill and Tombrello, 1996

Cahill et al. (1994), conducted field measurements of winds at Owens Lake, 80 kilometers southwest of the Racetrack. On the basis of these surveys, it was found that gusts of up to 40 meters per second were common occurrences at this locality. Furthermore, the extreme flatness of the terrain and smoothness of the dry lake surface results in a vertical compression of the atmospheric boundary layer (see Figure 2.15).

While maximum wind speeds over land surfaces are typically encountered approximately 1 meter above ground, the velocity gradient for flat playas is quite steep and vertically shallow. Bacon, Cahill and Tombrello reported that wind velocity 4 centimeters from the ground at Owens Lake was still 90% of wind speed measured 1 meter above the surface. They related these observations to the wind tunnel experiments reported by Schumm (1956), and noted that the pebbles tested were so small (i.e., they did not protrude up into the airflow substantially) that they could not be used as analogs to much larger rocks. Cobbles and boulders would be subjected to far greater forces, since they extend higher into the vertical zone of maximum wind speeds.

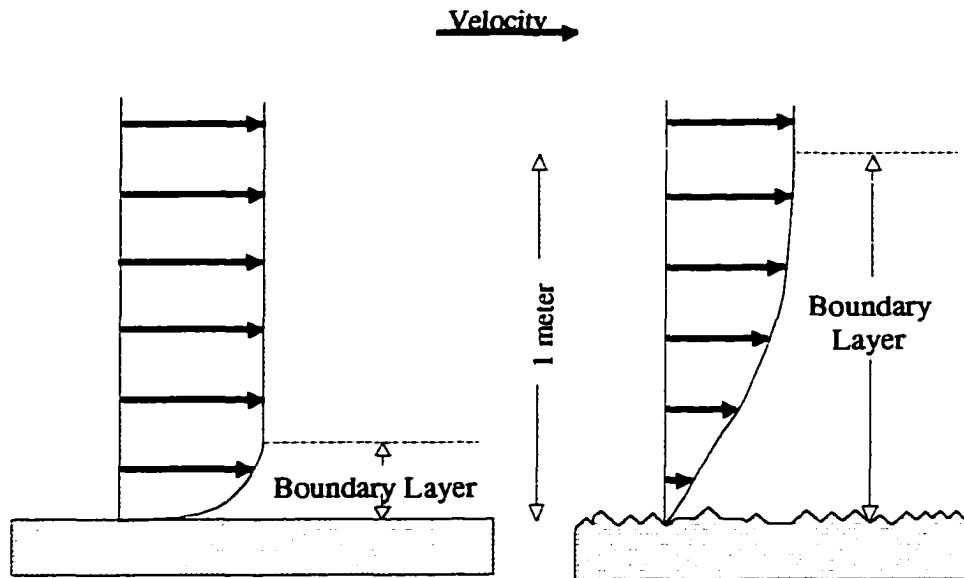


Figure 2.15: The velocity profile of wind above the ground is influenced by surface roughness of the terrain. As wind flows over flat, smooth surfaces such as Owens Lake and Racetrack Playa, maximum wind speeds are encountered only a few centimeters above the ground (left). Rough terrain promotes friction, increasing the height of the atmospheric boundary layer (right). (After Bacon, Cahill and Tombrello, 1996.)

Bacon, Cahill and Tombrello derived mathematical proofs to find the expression of force required to move an idealized rectangular rock:

$$F_D = \frac{1}{2} C_p V^2 A_f \quad \text{Eq. 2.10}$$

where C is the drag coefficient, A is the area of a cross-section of a rock, and p is the density of air ($\approx 1.29 \text{ kg/m}^3$). Note the equivalent formula as cited by W.E. Sharp (1960) (Eq. 2.6, page 36).

Bacon, Cahill and Tombrello (1996) explained that the drag coefficient C is a function of the shape of the rock; the value can be as low as 0.5 for highly rounded and smooth stones, to slightly greater than 1.0 for blocky, rectangular rocks. The frictional force may

be calculated by:

$$F_f = smg \quad \text{Eq. 2.11}$$

where s is the coefficient of static friction, m is the mass of the rock and g is the acceleration due to gravity. The frictional force must be less than the drag force for a rock to move. When the forces are equal ($F_D = F_f$), the coefficient of static friction may be computed by combining Equations 2.10 and 2.11.

$$s_T = \frac{1}{2} \frac{(C_p V^2 A_f)}{mg} \quad \text{Eq. 2.12}$$

Instead of solving for wind velocity (as was done by Shelton [1953], and Schumm [1956]) Bacon, Cahill and Tombrello, who had already established an estimate for probable wind speeds on the Racetrack substituted those values encountered on Owens Lake for ($V = 40$ meters per second) in Equation 2.12. They solved, instead, for the coefficient of static friction for selected rocks. The data they used were taken directly from Sharp and Carey (1976) (Appendix C).

The value for the cross-sectional area of Sharp and Carey's rocks was taken to be the mean, since rock orientation and wind direction would alter this quantity. This was computed as follows:

$$A_f = h\sqrt{lw} \quad \text{Eq. 2.13}$$

Substituting 0.8 for C (this is a mean value considering the variation in rock shapes) in

Equation 2.12, the team computed the threshold coefficient of friction (μ) for all rocks monitored by Sharp and Carey assuming wind forces of 80% of V (for rocks with low vertical profiles), and 100% V assuming extension up beyond the atmospheric boundary layer. The results of their calculations appear in Appendix D. When only 80% of the upper air velocity is considered, the mean coefficient of static friction for Sharp and Carey's rocks is 0.27; assuming the full force of wind, the average coefficient of static friction for this same subset is 0.42 (Bacon, Cahill and Tombrello, 1996). W.E. Sharp (1960) concluded that sliding friction values for rocks on a wet playa surface were from 0.145 to 0.26 (see page 37); since threshold coefficients are typically double the dynamic values of μ , the work of Bacon, Cahill and Tombrello is consistent with that of the earlier work, although their conclusions are not the same.

It is the opinion of Bacon, Cahill and Tombrello that a combination of high observed wind shear, compressed boundary layer and the likelihood of a slimy lubricant forming on the playa several hours to several days after a wetting event is enough to explain the sliding rock phenomena on the Racetrack.

2.13 Sharp and Carey versus Reid, Polissar and Williams, 1996

The wind vs. ice theories continue to be debated. A comment and reply were published in *Geology* with summary conclusions of each research team's (Sharp and Carey [1976], Reid et al., [1995]) investigations.

Much of what was written in these short papers reiterates earlier conclusions, yet they considered the more recent work by Cahill (1994) and Bacon, Cahill and Tombrello (1996). While Robert Sharp's comment that ice *may* transport rocks on occasion, but is

not a requisite condition for stones to move, John Reid's reply is less flexible. Taking the work of Bacon, Cahill and Tombrello (1996) into account, Reid et al. measured the wind profile on nearby North Panamint Playa and found no such collapse of the boundary layer. Wind speeds at a height of 5 centimeters were 50% of those at 1.5 meters. Reid et al. therefore maintained their earlier position in support of ice sheets.

Hence the conflicts continue. Even now, nearly a half century from the first detailed study, no one has been present to witness an event. Since no definitive spatial data existed for the playa (until this research), no complete baseline map of trails and rock positions had yet been published. The remote location of the Racetrack and the inhospitable conditions that must exist there during storms have been successful in keeping the motive mechanism a mystery.

Chapter 3

Digital Data Acquisition and Applications

As noted in Chapter 2, previous studies of the Racetrack Playa's sliding rocks relied on field mapping techniques available at the time. Kirk (1952) included highly detailed descriptions of rock trails and referenced them to nonspecific quadrants of the playa. The accurate plans by Stanley (1955), Sharp and Carey (1976) and Reid, et al. (1995) were drafted using manual field mapping methods. The object of these surveys was to test the prevailing hypotheses of rock motion, and it was therefore essential for these researchers to reference trails with respect to the locations of others. However, with the exception of some narrative descriptions or smaller-scale sketches, the furrows were not brought into the context of the surrounding terrain, nor were they located accurately or with respect to a known coordinate system and datum.

No complete survey of the trails had ever been attempted. Such an endeavor was nearly impossible to undertake given the isolation of the area, the complexity of trail networks, and the tedious, time-consuming efforts required for traditional mapping. The ability to overcome the obstacles of time, required resolution, and georeferencing for this and other mapping projects was made possible by the availability of Differential Global Positioning System technologies.

A complete map of sliding rock trails would be useful for comparison purposes: Parallelism between distant furrows has been the cornerstone of the ice raft theory (Stan-

ley, 1955; Reid, et al., 1995). However, describing the larger-scale processes that may be contributing to the patterns inscribed by the rocks requires observing the trails within the context of the surrounding terrain. While paper maps may be scaled to conform to existing topographic maps, this approach is descriptive rather than analytical. Data analysis is greatly enhanced by the ability to manipulate the spatial patterns in a variety of ways. Therefore, the use of digital elevation information to describe the Racetrack Basin was essential in this project. The existence of the Global Positioning System was both vital and timely for this research, since the navigational system became available for civilian cartographic applications only in the last decade.

3.1 Early Research, Development and Uses of GPS

The Global Positioning System (*GPS*) was designed by the United States Depart-

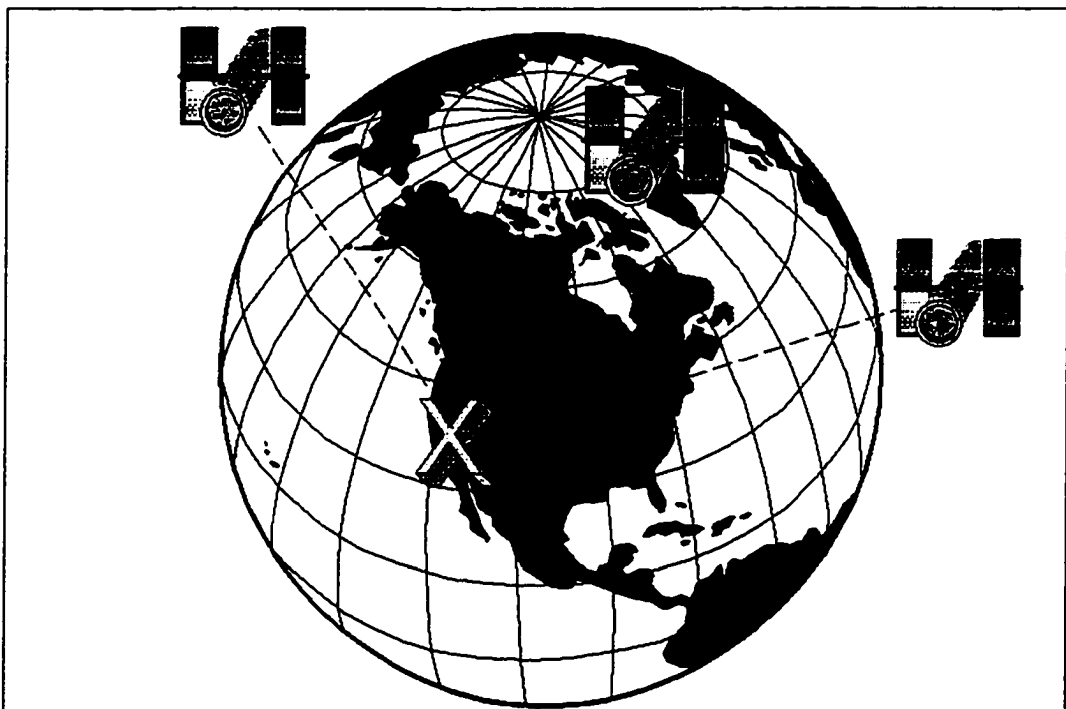


Figure 3.1 The Global Positioning System (GPS) provides new levels of accuracy and ease to field mapping, although the premise (the use of triangulation) is similar to that of traditional surveying methods.

ment of Defense for military navigation and guidance. First proposed as early as 1940, the National Defense Research Council suggested that a navigation system combining radio signals with accurate time measurements could be deployed at some point in the future (Beadles, 1996). LORAN, the first all-weather navigation system, was developed at the Massachusetts Institute of Technology soon after and was used during World War II to guide allied forces. After wartime the Omega system was developed to cover a greater portion of the globe. It utilized lower frequencies to attain its more comprehensive network, but sacrificed accuracy as a result (Parkinson, 1994).

After the launch of Sputnik-I by the Soviet Union in 1957, it was proven that a satellite's orbital parameters could be gleaned by measuring the doppler shift of its on-board radio transmitter. It followed that if precise orbital characteristics might be determined from the ground, then the reverse is also possible: ground positions might be calculated from an orbiter's locational data (Herring, 1996). Following through on this concept, the United States launched a navigation satellite called TRANSIT 1A in September 1959, but the payload failed to make orbit. Subsequent attempts to deploy TRANSIT satellites were successful in 1960 and 1961, and by mid-1962 the U.S. Navy was using this system to accurately locate ballistic missile-carrying submarines. The U.S. Army launched its first navigation and positioning satellite, SECOR 1, in January 1964; seven more SECOR orbiters were deployed in 1965 and 1966. The Soviet Union developed TSYKLON, its first navigation satellite, in 1967, and placed it in low-Earth orbit in November 1967 (Beadles, 1996). Table 3.1 shows the comparative accuracies and ranges of several ancient, historical and modern navigation systems.

Table 3.1: A Chronology of Selected Navigation Aids (Dias, 1996)

Type	Accuracy	Range
Celestial	?	Worldwide, clear skies required
Triangulation	Depends on Range	1000 to 1500 meters
LORAN-C	60-300 feet (18-90 meters)	1000 to 1500 meters
Deca	90 feet (day), 300 feet (night)	100+ miles
VOR	600 feet	~200 miles
TACAN	200 feet	200 miles
Omega	2 - 4 nautical miles	worldwide
TRANSIT (U.S. Navy)	35 meters	worldwide (once per 6 hours)
NAVSTAR GPS	17-100 meters	worldwide 24 hours per day

3.2 The Evolution of NAVSTAR

In 1969 the first TIMATION satellite was launched by the U.S. Navy. By April 1973 the U.S. Air Force requested the Defense System Acquisition Council to combine its own navigation system, *621B 3-d*, with TIMATION in an effort to develop a Defense Navigation Satellite System (DNSS). The comprehensive system was approved in December of that year, combining the best elements of all existing radionavigation technologies. Ultimately, the DNSS would be renamed NAVSTAR (*Navigation Satellite Timing and Ranging*).

Engineered by Rockwell International, the next generation of NAVSTAR satellites was launched beginning in 1978, and over thirty of these space vehicles (SVs) have been placed into orbit since then. NAVSTAR orbiters have provided an almost continuous

matrix of active navigational instruments. There have been only two launch failures (SVN 7 on December 18, 1981 and SVN 42 on January 17, 1997) and one near destruction of NAVSTAR hardware (NAVSTAR 33 was almost destroyed by protesters who broke into Rockwell's facility in 1992, but it was repaired and deployed in 1996) (Beadles, 1996). With an average life-span of seven years, many of the more recent launches were necessary to replace older hardware. The last of the "first block" of NAVSTAR satellites was launched in 1985, but augmentation of the system continues through the 1990s.

There are three distinct groups of NAVSTAR satellites, with one sub-group, designated as blocks. The block I satellites were intended for system testing. The block II satellites were the first fully functional orbiters; they possess radiation-hardened electronics, allowing for longer lifetimes in space, onboard cesium atomic clocks, allowing for precision time keeping as well as the ability to implement a type random error generation known as Selective Availability (SA). A block II satellite can detect certain error conditions, automatically transmitting a code indicating that it is out of service, and they can operate for 3.5 days between corrections from the ground. A sub-group of this generation of instruments, known as block IIa can continue to operate for 180 days between uploads from the ground.

The latest satellites, the block IIR versions, include autonomous navigation. These satellites can operate for 180 days between uploads and can generate their own navigation information. Thus, the accuracy of the system can be maintained longer between uploads. Each satellite in the matrix has two identifying numbers. First is the NAVSTAR number which identifies the specific satellite hardware. Second is the SV number. This number corresponds to the launch order.

Initial Operational Capability was declared on December 8, 1993 when 24 GPS satellites were functioning. At that point, it was possible to use the system, although coverage for all locations at all times was incomplete. The U.S. Air Force Space Command formally declared the GPS satellite constellation as having met the requirement for Full Operational Capability on April 27, 1995. In addition to the functioning SVs there are active spares whose orbits may be altered remotely in the event of satellite malfunction (Beadles, 1996).

All SVs are in 20,180 kilometer altitude orbits of roughly 12 hour periods. Each satellite repeats the same track over any point every 24 hours (four minutes earlier each day). A minimum of four satellites are equally spaced (at least 60 degrees apart) in one of six orbital planes, inclined at 55 degrees with respect to the polar plane. This matrix ensures that every point on Earth has between five and nine satellites above the horizon at all times (Dias, 1996).

The NAVSTAR satellite constellation comprises only one of three interdependent system components, and is known as the “space segment.” The GPS “control segment” consists of a network of tracking stations located around the world. Five monitoring stations (in Hawaii, Kwajalein, Ascension Island, Diego Garcia and Colorado) continually track all satellites in view and log ranging data. The Master Control Station at Falcon Air Force Base east of Colorado Springs, Colorado processes the incoming data to determine individual satellites’ orbits. Ground antennas located at Ascension Island, Diego Garcia and Kwajalein then update the SVs’ navigation message by uploading orbital data (ephemeris) and clock corrections. This information is beamed to each orbiter once or twice daily (Dias, 1996).

The GPS “user segment” is composed of worldwide end-users. GPS receivers convert SV signals into position, velocity and time estimates; uses include navigation, positioning, time dissemination and other research (Dana, 1996). Constellation geometry ensures that all points on Earth have at least five satellites above the horizon at all times, yet only four are required for three-dimensional position and time computation. Local masks such as mountains, buildings or vegetation (specifically tree canopy) may block one or more satellites from view. Hence, having five, six or more SVs in sight greatly increases the chances of successfully obtaining a location fix.

3.3 GLONASS

Concurrent to the implementation of the NAVSTAR system, the first phase of GLONASS (Global Navigation Satellite System) deployment began in 1982 with the launch of Cosmos 1414 by the Soviet Union. Launches continued through the 1980s and 1990s to complete a constellation of 24 orbiters, eight in each of three orbital planes. Circular orbits of 19,100 kilometers at inclinations of 65 degrees allow for 11.25 hour periods (Johnson, 1994). Table 3.2 shows a comparison of GPS and GLONASS systems.

Table 3.2: GPS and GLONASS Systems Comparisons. (Dias, 1996)

Parameter	GPS	GLONASS
Orbit height	20,180 kilometers	19,100 kilometers
Orbit radius	26,500 kilometers	25,510 kilometers
Satellite Ephemeris	Keplerian orbital elements	Geocentric cartesian coordinates
Orbit inclination	55 ± 3 degrees	64.8 degrees, with $< 5^\circ$ drift
Orbital planes	6	3
Number of satellites per orbital path	4	8
Separation of satellites in plane	90 degrees	45 degrees
Period	718 minutes	676 minutes
Position reference	WGS 84	SGS 85
C/A SP accuracy, SA on	100 meters horizontal, 156 meters vertical, 340×10^{-9} s.	57 - 70 meters horizontal, 70 meters vertical, 10^{-6} s.
C/A SP accuracy, SA off	17.8 meters horizontal, 27.7 meters vertical, 200×10^{-9} s.	57 - 70 meters horizontal, 70 meters vertical, 10^{-6} s
Lifetime	7.5 years	5 - 7 years
Number of spare satellites	3	3

3.4 Standard and Precision Positioning Service

Both NAVSTAR and GLONASS provide two levels of service, for civilian and military applications. In 1983, an interagency study by the U.S. Secretary of Defense, Joint Chiefs of Staff, Defense Mapping Agency and others found that the accuracy of positional data possible using the NAVSTAR system posed a threat to national security. It was agreed that since the Precise Positioning Service (PPS) could be used by political enemies

against the United States, the signal should be degraded for non-military users. The Standard Positioning Service (*SPS*), with horizontal accuracies of 100 meters, was introduced for use by the general public; the more accurate PPS was reserved for military use.

NAVSTAR instruments transmit two microwave carrier signals: the L1 frequency (1575.42 MHz) carries the navigation message and Standard Positioning Signal (*SPS*); the L2 band (1227.60 MHz) is used to detect ionospheric delays for Precision Position Signal (*PPS*) receivers (Dana, 1996).

The Standard Positioning Service (*SPS*) is a locational and timing service available to all GPS users on a continuous, global basis. *SPS* is provided on the GPS L1 frequency which contains a coarse acquisition (*C/A*) code and a navigation data message. *SPS* provides a positioning accuracy of 100 meters horizontally, 156 meters vertically and time transfer accuracy to UTC within 340 nanoseconds.

The Precise Positioning Service (*PPS*) is a highly accurate military locational, velocity and timing service available worldwide to users authorized by the United States. Precision code-capable military user equipment provides a predictable positioning accuracy of at least 22 meters horizontally, 27.7 meters vertically and time transfer accuracy within 200 nanoseconds. Designed primarily for U.S. military use, *PPS* is transmitted on the L1 and L2 frequencies. It is unavailable to unauthorized users by the use of cryptography. The precision code is available to U.S. military and U.S. Federal Government users, and to others with special permission (Dana, 1996).

Three pseudo-random noise (*PRN*) ranging codes are in use. The coarse acquisition (*C/A*) code has a 1.023 MHz chip rate, a period of one millisecond and is used primarily to acquire the precision code. The precision (*P*) code has a 10.23 MHz rate, a period

of seven days and is the principal navigation ranging code. An anti-spoofing device guards against fake transmissions of satellite data by encrypting the P-code to form the Y-code.

The Russian Federation's GLONASS satellites transmit two L frequency waves, at 1609 and 1251 MHz. Both standard precision (SP) and high precision (HP) navigation signals are carried, but the HP code is encrypted to prevent use by non-military end-users (Dias, 1996).

3.5 Basic Principles of GPS Navigation

The fundamentals by which this technologically-advanced spaceborne system works are actually quite simple. Classical trigonometry is the basis for ground-based surveying, and it is also the technique employed by GPS mapping. And just as eighteenth century navigation was revolutionized by the development of the chronometer, highly accurate time-keeping is analogously essential to GPS location fixing.

Distances from satellite vehicles to an Earth-based receiver are computed by multiplying the one-way travel time by the speed of propagation, c . Even when considering the relatively high-altitude orbits of the satellites, travel times are on the order of 10^{-2} seconds. Due to the short periods involved, highly precise clocks capable of accuracies in the nano-second (10^{-9} s) range are used. Each receiver and SV generate identical digital codes simultaneously (Figure 3.2). Sequences are complicated digital pseudo-random pulses that repeat themselves every millisecond. Thus the exact time that a satellite propagated a particular trademark signal can be extrapolated back from the time it is received on the ground. Since all clocks are precisely synchronized the absolute travel time between sat-

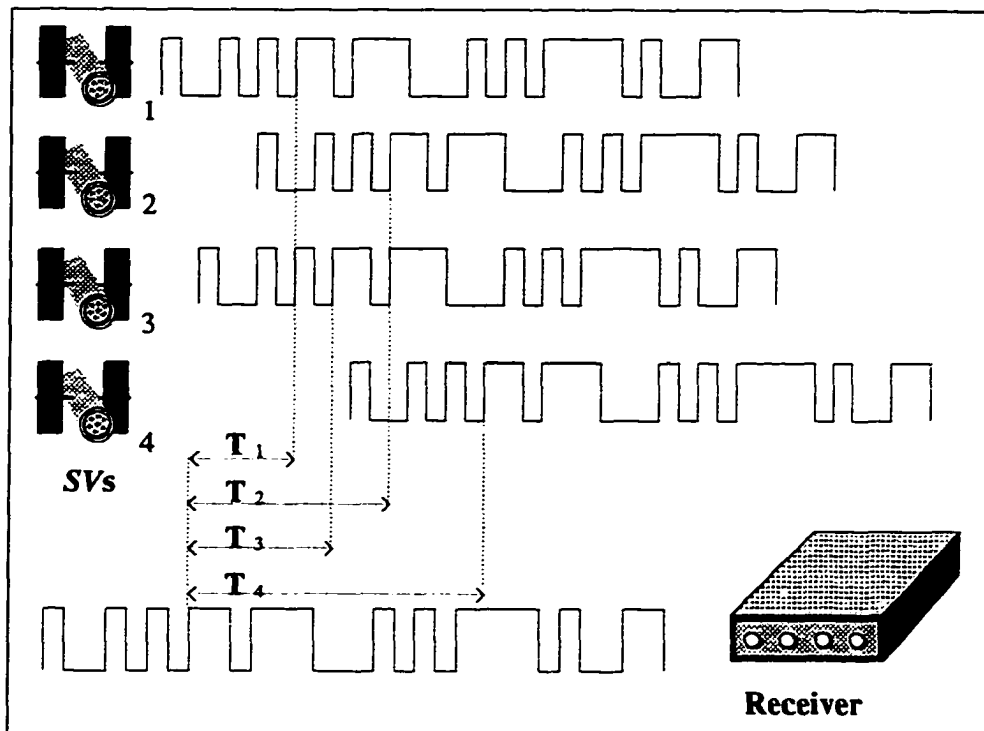


Figure 3.2: Pseudo-random codes are simultaneously generated by space vehicles and ground-based receivers. The exact time difference between signal propagation and signal reception (ΔT) is used to compute the distance to each satellite.

ellite and receiver is calculated. This time difference (ΔT) is computed for each satellite in range, and is then translated into distance.

Orbiters are instrumented with four atomic clocks apiece; receivers are not as sophisticated. To compensate for this shortcoming, one extra satellite range calculation is made. Since at least four measurements are usually taken, the term *triangulation* is somewhat inappropriate to describe the technique, but the principles are the same (see Figure 3.3). While a two-dimensional fix (X , Y only) may be attained with just three satellites, a minimum of four calculations must be made to gather the two horizontal coordinates (X and Y); the vertical measurement (Z) and a time component.

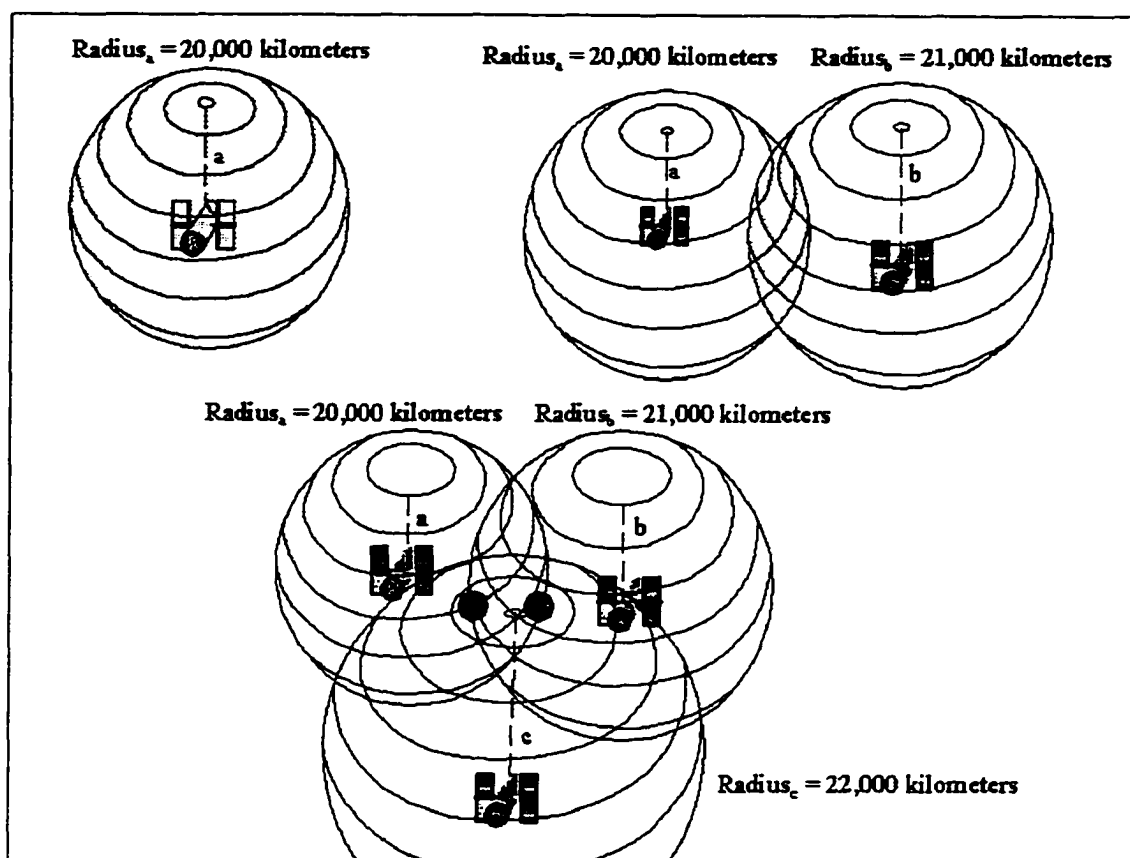


Figure 3.3: Global positioning satellites orbit Earth in fixed, known paths. When an unknown location is calculated to be 20,000 km from one of these satellites (upper left), that point may exist anywhere in space on a spherical surface with a 20,000 km. radius. If a point's distance to **two** satellites is known, its position may be confined to the area of overlap of the two satellites' "radius-bounding spheres" (upper right). When distances to **three** satellites are computed, the location is limited to one of two points (large gray dots, lower diagram). Since only one of these points will also intersect Earth's surface, the observer's place on the globe is known. (After Hurn, 1989)

3.6 GPS Receiver Design

The need for at least four streams of simultaneously collected data altered the design of GPS receivers. Dedicating one channel to each of four satellites requires at least a four-channel receiver. It is possible to obtain fairly accurate information with a single-channel receiver by cycling through four or more SVs, but these instruments lack the luxury of instantaneous data collection, and are most unreliable in velocity calculations.

Adding a second channel doubles a system's inherent signal-to-noise ratio, and such receivers can therefore perform under more adverse conditions (i.e., satellite tracking closer to the horizon, etc.). One channel continuously monitors positional data while the other locates the next satellite in a series. Three channel receivers offer a compromise: two bands lock on to a satellite in the sequence while the third performs the time measurement. This can hasten the sampling sequence significantly since continuous updates are always available. An added benefit of a multi-channel receivers is that they may be programmed to track up to eight SVs so that if one satellite is blocked, another may be substituted with minimal interruption. Equipment costs have decreased significantly making these low-end receivers widely available (Hurn, 1989).

Most high-end equipment used for mapping utilizes 8- 10- or 12-channel receivers, especially when sub-meter resolution is desired. By tracking **all** satellites above the horizon, position uncertainty is minimized; multi-channel "continuous" receivers obtain nominal errors whereas "sequencing" receivers rely on calculating the four satellites positioned for the *best* fix possible. With eight channels, a receiver can double the signal-to-noise ratio of a four-channel system, and can quadruple that of a two-channel system. Accuracy is also enhanced by comparing bands and calibrating interchannel biases.

Most recently, combined GPS/GLONASS receivers have been developed. Increasing the total number of usable SVs to 48, with as many as fifteen above the horizon at any time, provides the end-user with even more options. The possibility of obtaining signals from at least three satellites in the combined matrix is greatly increased, even in canyons, urban corridors, construction sites and other places where GPS mapping was previously impossible.

3.7 Inherent Sources of Error

GPS error sources range from **random noise**, **bias** and large-scale **blunders**.

Noise errors usually amount to locational inaccuracies of up to a few meters, and are caused by receiver noise and pseudo random noise.

Bias errors result primarily from the addition of the Selective Availability signals. The intentional degradation of the signal by S/A amounts to approximately two standard deviations of the potential C/A code resolution (i.e., from under 30 meters to about 100 meters). All NAVSTAR satellites generate different S/A codes; hence this is a changing and low-frequency bias. Other bias errors include clock inaccuracies which, if left uncorrected by ground control, may result in minor (up to one-meter) errors. Atmospheric dynamics can account for errors of over 10 meters, with tropospheric factors such as changes in air temperature, barometric pressure and humidity accounting for only one meter or less. Ionospheric delays of up to 10 meters are possible due to upper atmospheric aberrations. Multipath bias errors, generally sub-meter in range, are frequently unavoidable. They are caused by interference of signals by near-receiver reflectance of waves, or other physical obstacles in the line-of-sight between the receiver and SVs.

Blunders are systematic errors that may result from user mistakes (including incorrect geodetic datum selection), software problems, receiver failures or control segment mistakes. Computer or human error can cause position solution inaccuracies from one meter to over two orders of magnitude greater.

3.8 Accuracy Considerations During Data Collection

Errors are magnified by the range vector differences between the receiver and sat-

ellite. The Geometric Dilution of Precision (*GDOP*) is a numerical value computed from the spatial relationships between the receiver position and the locations of the satellites within line of sight. Acceptable GDOPs (corresponding to small values) occur when angles between the receiver and SVs are high, and a large unit-vector volume results (see Figure 3.4).

The total GDOP value is a sum of its components:

- PDOP, the Position Dilution of Precision (a three-dimensional measure);
- HDOP, the Horizontal Position of Precision (X-Y coordinates only);
- VDOP, the Vertical Dilution of Precision (altitude only);
- TDOP, the Time Precision of Precision

Each value may be individually computed, but all are results of the navigation covariance matrix and are therefore interrelated (Dana, 1996).

3.9 Differential GPS

Increased accuracy demands necessitated the emergence of alternative strategies to enhance data quality. Differential GPS (*DGPS*) involves the use of regular GPS with an

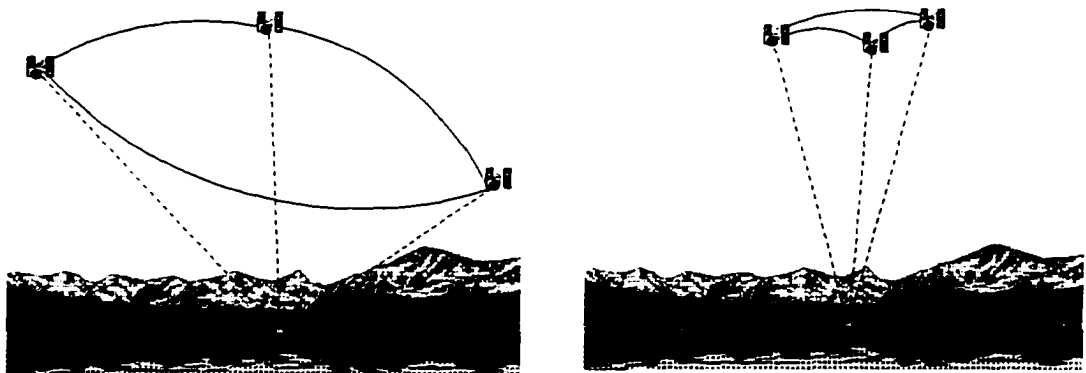


Figure 3.4: Geometric Dilution of Precision (GDOP) is affected most by satellite geometry. The drawing on the left shows an ideal satellite configuration for accurate field measurements (corresponding to low GDOP values). When SVs move to within acute angles from one another (right), positional accuracy is hindered—even if more than three satellites are within the field of view.

additional correction signal added. DGPS uses a reference station at a known point (also called a *base station*) to calculate and correct bias errors. The reference station computes corrections for each satellite signal and broadcasts these corrections to the remote, or roving, GPS receiver in real-time, or via post-processing. The field receiver then applies the corrections to each satellite used to compute its fix.

Logging instantaneous DGPS coordinates may be accomplished using the corrections of any number of base stations. The United States Coast Guard and Army Corps of Engineers continuously transmit differential corrections via radio beacons. Coverage is not geographically continuous, yet most of the East Coast, the Great Lakes, some of the West Coast and many inland waterways are within range. Several commercial FM radio stations transmit corrections on sub-carriers for subscribers; coverage is sporadic and for a fee. Geostationary satellites are sometimes used to relay differential adjustments instantaneously uploaded from a ground control base station. Problems with these methods include the possibility of long baselines between the remote base station and rover (which degrades the ultimate accuracy of the dataset) and the prospect of recording from a different group of SVs than the one visible to the field area.

Portable base stations are useful when the above options are impractical or unrealistic. A “sister receiver” is established at a nearby fixed point (usually a known location such as a benchmark). The base station continually transmits or logs the Selective Availability deviations for real-time or post-processed corrections. When raw fixes are merged with the corrective data from the base station, highly accurate location information can be assigned to each point in the rover file. A summary of plausible accuracies is outlined in Table 3.3.

DGPS removes common-mode errors (i.e., common to both reference and remote receivers) but does not filter all error sources (e.g., multipath, receiver noise, etc.) (Dana, 1996). Minimization of these factors continues as hardware developments (e.g., “choked” antennas) and adapted processing methods are introduced (Weill, 1997). Hence, despite the multiple sources of error DGPS mapping methods provide the user with a highly accurate alternative to traditional surveying.

Table 3.3: Attainable Accuracies of Various GPS Techniques (after Langley, 1994)

Desired Resolution	Equipment Needs
300 meters - 100 meters	This is the accuracy range that the Department of Defense guarantees from the Standard Positioning Service (SPS), the only service commonly available to civilian users.
25 meters - 10 meters	Inexpensive handheld receivers with basic DGPS can usually achieve accuracies in this range.
5 meters - 1 meter	Better handheld receivers and mapping grade receivers can achieve this level of accuracy.
1 meter - 10 centimeters	Better quality mapping receivers and low-end surveying equipment can attain this level of accuracy. Such receivers will generally use carrier phase measurement techniques instead of code-based solutions. Users requiring greater accuracy can take long observations (between 20 seconds and 2 hours) and by surveying multiple points as a network and using network adjustment routines. Sub-centimeter accuracies are possible using these techniques.
10 centimeter to sub-centimeter	High end surveying receivers and geodetic receivers are used to reach this level of accuracy. Receivers of this class use carrier phase measurement techniques and generally both GPS frequencies. A relatively new technique known as ambiguity resolution on the fly (<i>AROF</i>) allows receivers to start producing high-quality solutions very quickly (within 40 seconds) without complicated initialization procedures.

The Global Positioning System is now a widely-used and rapidly-evolving navigational tool. Field surveying using DGPS technology provides the end-user with a highly

accurate spatial data set, however due to the geometry of satellites' orbits over Earth's surface, elevation resolution is roughly twice that of locational data. Even so, measurements in the *Z*-axis direction may be achieved to sub-meter resolution with high-end equipment. Luckily, the availability of existing digital elevation information circumvents acquisition shortcomings.

3.10 Digital Elevation Data

Any digital representation of the continuous variation of relief over space is known as a digital elevation model (DEM) (Burrough, 1986). Traditionally, terrain has been depicted by *line models*, such as contour map representation. The U.S. Geological Survey (USGS) archives and sells complete contour map coverage for the United States at several scales. Original data were collected by manual survey teams and updated sporadically, most recently with the aid of regional aerial photographs. These maps have been digitized and thereby transformed into *point models*, in which elevations of point locations compose an altitude matrix.

There are numerous significant advantages to using terrain data in digital form. Among the most pertinent to the Racetrack Playa mapping project are the following uses, as outlined by Burrough (1986):

- three-dimensional display of landforms,
- analysis of cross-country visibility,
- statistical terrain analysis,
- computation and production of slope and aspect maps for geomorphological study,
- simulation modeling of landscape processes.

Automated contouring and hillshading routines can transform the raster array back into a continuous surface, thus reversing the process initially used to adapt the data to dig-

ital format. Paper maps, while essential in the field and helpful in the lab, simply do not allow for the versatility of digital products. For example, Figure 3.5 shows the Ubehebe Peak DEM header file, and Figure 3.6 shows examples of images created with this one data set. A discussion of the specific analytical processes undertaken for this mapping project is found in Chapter 6.

There are several USGS Digital Elevation Model (DEM) formats based on the extents of the source maps (7.5-minute, 15-minute, 30-minute and 1-degree) (U.S. Geological Survey, 1993). The most frequently used and easily accessible scales are the 1:250,000 (1-degree) and 1:24,000 (7.5 minute) data sets. Complete continuous coverage exists for the United States in the smaller scale (1-degree) format, but digitization of every 7.5-minute quadrangle has not been accomplished to date.

One-degree DEMs are ASCII files of 1,201 rows and 1,201 columns of 3 arc-second grid cell elevations in meters. These data are very similar to the Defense Mapping Agency's Digital Terrain Elevation Data (DTED) data, and in fact are derived from them (Clarke, 1995). Elevations are referenced to the geographic coordinate system (latitude/longitude) of the World Geodetic System 1972 Datum (WGS 72) or World Geodetic System of 1984 (WGS 84) (U.S. Geological Survey, 1993). All United States 1-degree DEMs are available in the public domain, and are downloadable over the Internet through the USGS home page. These data sets are useful when coarse horizontal resolution (approximately 90 x 90 meters) does not preclude the type of analysis desired.

For most terrain modeling, however, 7.5-minute DEMs are more useful. These data sets are based on the USGS 7.5-minute topographic quadrangles, referenced horizontally to the Universal Transverse Mercator (UTM) coordinate system. Reference datum

may be either North American Datum of 1927 (NAD 27) or North American Datum of 1983 (NAD 83) for areas excluding Hawaii and Puerto Rico. As with the smaller-scale models, these data sets are flat files of ASCII elevation values assigned to rows and columns of non-uniform extent (this is due to the variable angle between the quadrangle's true north and grid north of the UTM coordinate system). Numerical altitude quantities are stored as feet (for low-relief terrain) or meters (when the contour interval of the original map was greater than 10 feet) (U.S. Geological Survey, 1993). As with the 1-degree DEMs, 7.5-minute data sets are available through the USGS, but coverage is not continuous. The larger-scale data are usually supplied by the USGS on CD-ROM or tape for a nominal fee. Since grid cell areas are greatly reduced for these data sets (1-degree DEM matrix cells cover areas nine times larger), 7.5-minute data are desirable when more accurate surface interpolation is required.

3.11 Limitations of DEMs

While more versatile than printed maps, digital terrain data are not without shortcomings. Since DEMs are digitally encoded *sample* measurements of the surface elevation of topography (Clarke, 1995), one has to consider the sampling accuracy of the derived data set. In the case of 7.5-minute DEMs, altitudes are expressed as single integers for areas encompassing 900 m^2 . For relatively low-relief landscapes, the approximation of the assigned quantity to *all* points in the bounding square is greatest. However, in areas of great elevation variation, each pixel's value is a mere average of all point heights in the 30×30 meter area. Therefore, topographic detail is lost by conversion to digital format. Of course, inferred elevations of all point locations may be obtained by an interpola-

tion algorithm, but the accuracy of these calculations is questionable, especially in mountainous or otherwise rough terrain.

Burrough (1986) discusses other trade-offs of the use of raster data. Among disadvantages, he specifies:

- the large amount of data redundancy in areas of uniform terrain,
- the inability to adapt to areas of differing relief complexity without changing the grid size, and
- the exaggerated emphasis along the axes of the grid for certain kinds of computation such as line-of-sight calculations.

Several methods have been introduced to counteract the data redundancy and data storage issues. Techniques such as file compression and Morton sequencing can greatly reduce the volume of data associated with raster elevation files, particularly in areas of low relief (Clarke, 1995).

3.12 DEM Data Accuracy

The USGS classifies its digital elevation products according to three grades of accuracy. They are categorized as **Level 1**, **Level 2**, and **Level 3** DEMs.

Level 1 designation is reserved for 7.5-minute DEMs or equivalents that are derived from scanning National High-Altitude Photography Program or National Aerial Photography Program photographs (U.S. Geological Survey, 1993). For digitized 7.5-minute quadrangles, a vertical root mean square error (*RMSE*) of 7 meters is the desired accuracy goal, but the file may contain errors up to 15 meters maximum. When the source data are derived photogrammetrically, this level of accuracy (7 to 15 meter *RMSE*) is considered an intermediate product, which will soon be replaced by higher accuracy DEMs (U.S. Geological Survey, 1993).

Level 2 data sets are those that have been processed, smoothed and edited to remove systematic errors. The maximum allowable RMSE for this category corresponds to one-half the contour interval of the source map, and no errors exceeding one contour interval in magnitude are tolerated (U.S. Geological Survey, 1993).

Level 3 DEMs are acquired from USGS Digital Line Graphs (*DLGs*). The maximum allowable RMSE for this class is one-third the contour interval, with no errors greater than two-thirds the contour interval permitted. (U.S. Geological Survey, 1993).

As of 1993, all USGS 1-degree DEMs fell under Level 3 standards; most 7.5-minute DEMs were categorized as Level 1 products. The USGS planned for most future 7.5-minute DEMs to adhere to Level 2 criteria, as many were to be generated by interpolating digital contours.

```

UBEHEBE PEAK, CA  DEM GENERATED WITH LT4X
      3      RMMC      2      1      1      11
0.000000000000000D+00  0.000000000000000D+00
0.000000000000000D+00  0.000000000000000D+00
0.000000000000000D+00  0.000000000000000D+00
0.000000000000000D+00  0.000000000000000D+00
0.000000000000000D+00      2      2      4
0.444116389113445D+06  0.405325346531635D+07
0.444206758700486D+06  0.406711929637851D+07
0.455365498355228D+06  0.406705374735999D+07
0.455293204174015D+06  0.405318800209275D+07
0.595000000000000D+03  0.188200000000000D+04
0.000000000000000D+00
10.300000E+020.300000E+020.100000E+01      1  375  00
40187009412I5 0 2 1  1  0      1      1  18      1
0.444120000000000D+06  0.405327000000000D+07
0.000000000000000D+00  0.648000000000000D+03
0.668000000000000D+03  668  666  665  663  662  662
661  660  659  658  657  656  654  653  652  651
649  648

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Figure 3.5: Header file for the USGS Ubehebe Peak DEM, which indicates that this data set was made from a DLG overlay (process 3) at the Rocky Mountain Mapping Center (RMMC). It is a level 2 DEM, using a regular pattern (1) and UTM (1) coordinates, zone 11. UTM codes for all four corners follow the map projection parameters, all set to zero. The last line in this excerpt indicates elevations for the first row, in meters. Figure 3.6 (next page) shows several graphic representations of this data.

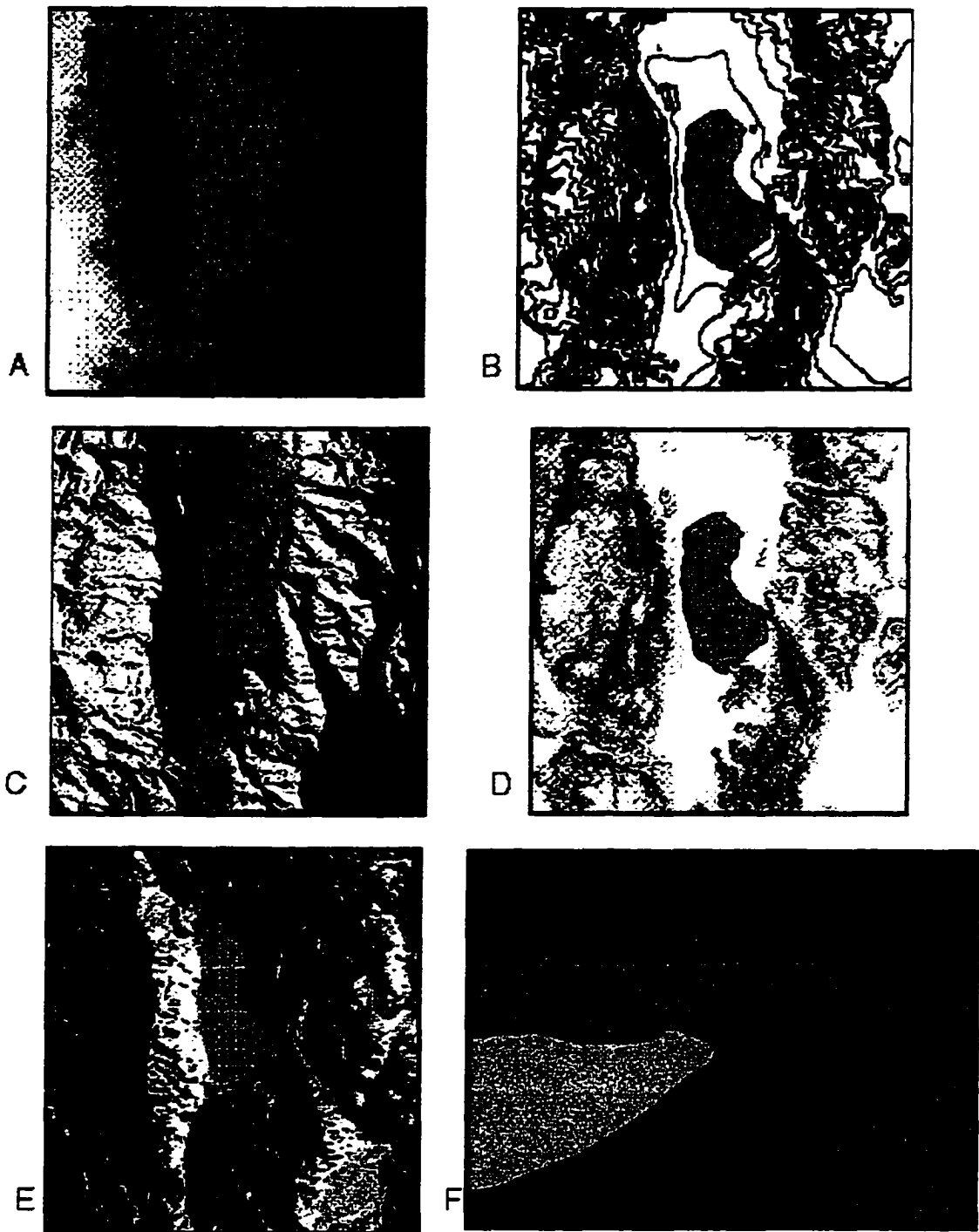


Figure 3.6: Using the Ubehebe Peak DEM (see Figure 3.5, previous page) the following derived images were created: A) Arc/Info grid with hypsometric tinting; B) Contour map (contour interval 50 meters); C) Hillshaded relief map; D) Slope map; E) Aspect map; F) Perspective View from Ubehebe Peak.

Chapter 4

Racetrack and Related Playa Field Investigations

4.1 Racetrack Playa: Preliminary Visits

The Racetrack Playa was visited as part of this research on eighteen occasions, the first time as a casual park visit in February 1993. Subsequent investigative expeditions took place in April, July and December 1994; August 1995; February, July-August 1996; December 1996; March and August 1997.

The first trip to the Racetrack was merely to observe the sliding rock oddities, as recommended by a park ranger. The winter of 1992-93 was unusually wet throughout the Southwest, and Death Valley was not immune from the excess moisture. The first visit to the Racetrack took place on a stormy day; snow was falling at higher elevations to the north along the Racetrack Road, but at the playa the precipitation was falling as rain.

The Racetrack is usually approached by road from the north; for the last 10 kilometers of the ride the road descends a gentle alluvial fan that encroaches the playa at its northernmost extent. There are two parking areas: One near the Grandstand and the Ubehebe Peak trailhead, and another farther south, closer to the majority of the sliding rocks. Arriving around mid-day, the temperatures were only slightly above freezing and blustery winds added to the generally inhospitable conditions. The required four-wheel drive

vehicle was parked at the second (more southerly) turn-off.

At this “parking area” (simply a widened segment of the unpaved road) there is a National Park Service interpretive sign. It describes the work of Sharp and Carey (see Section “2.10 Sharp and Carey, 1976” on page 42), and it provides tourists with information about general trail morphology, including one sighting of a perfectly circular route. A cursory review of the ice-sheet and wind-only theories is included in the text, yet no sketches or photographs of the trails are depicted.

One needs to walk across a ditch (dug by the park service in 1969) and over one kilometer away from the road in order to observe the densest accumulations of sliding rocks. Walking was quite difficult as the playa surface was thoroughly saturated. The fine-grained muds provided little friction for the seemingly long journey. Water was apparently infiltrating the playa surface, mostly through the network of desiccation cracks. Accumulations were not significant enough to judge the playa’s horizontality.

Approaching some of the boulders, one could see faint trails that served as reservoirs for accumulating water. Since the playa surface was totally flooded it was difficult to see the furrows, but they were nonetheless very impressive. The trails crossed and wove into one another in patterns that were difficult to interpret. Given the physical circumstances of the day they were difficult to follow. Even so, over thirty photographic slides recorded the unusual features, and the visit sparked the curiosity of this author, spawning future visits.

Returning to the Furnace Creek Visitor Center and Death Valley Museum at Park Headquarters, several rangers were queried about existing trail maps and scientific papers about the phenomena. Surprisingly, there was little information available to the casual vis-

itor, a revelation which only heightened curiosity.

Subsequent visits in April, July and December 1994, and August 1995 were used to observe and record photographic evidence of rock motion, but no long-term organized monitoring efforts were undertaken. It was during this time that the idea of producing a complete map of the lineaments developed.

4.2 Racetrack Playa: February, 1996

The first trip specifically targeted for scientific field investigations took place in February 1996. Having only one week to conduct research allowed for some activities, but not others. This visit was a focused “needs assessment” expedition, targeted at evaluating the projected survey mission planned for the summer. Despite the limited time frame, several significant observations were documented.

The northern, eastern and southern playa boundaries were traversed (Figure 4.1, page 83); descriptive notes were recorded in a field notebook. The western edge of the playa parallels the unpaved road, between which lies the park service-dug trench. Spot locations corresponding to field observations were obtained using a handheld GPS receiver, subject to the 100-meter Selective Availability error. However, since the object of this survey was to obtain a general description of the playa and *not* to map it, this resolution sufficed.

4.2.1 Meteorological Data

Through the visit, temperature data were logged by the National Park Service at four locations; our team recorded minimum and maximum temperatures at the Racetrack Playa using a U-tube mercury thermometer calibrated to Fahrenheit degrees. The instru-

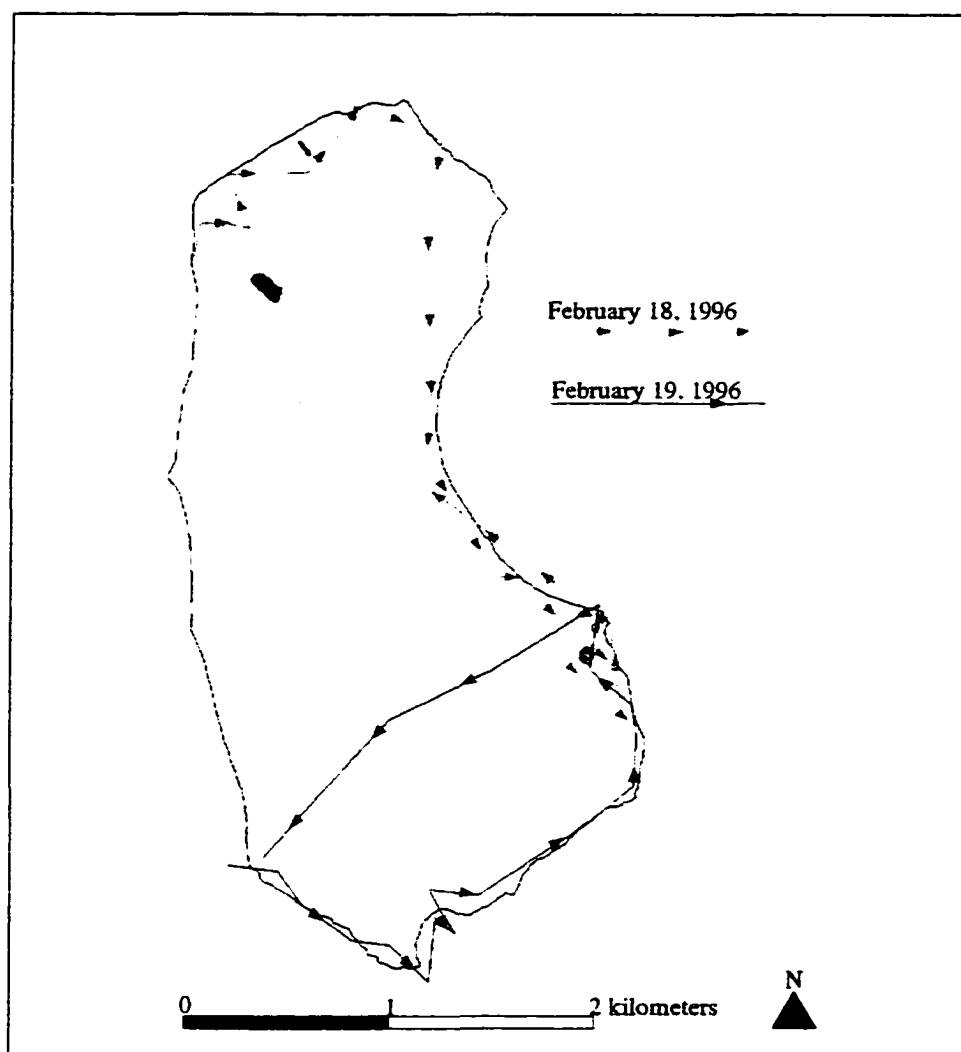


Figure 4.1: The Racetrack Playa was traversed and described on February 18-19, 1996. The two paths taken are indicated. The dashed line running southeast-northwest was the straight-line route back to the vehicle on the first day. (The absence of arrows indicates that no meteorological data were collected along that transect.)

ment was secured in a sun-sheltered enclosure, and checked each day of the survey. Data for other areas within the national park may be used for comparison (Table 4.1).

Table 4.1: Air temperatures in Death Valley National Park, February 1996

Date	Minimum/Maximum Temperatures				
	Furnace Creek EL. 55m/-180 ft	Scotty's Castle EL. 914 m/ 3000 ft	Stovepipe Wells EL. 0 m/0 ft	Wildrose EL. 1312 m/ 4000 ft	Racetrack Playa EL. 1131 m/ 3708 ft
2/18/96	28°/11° C 83°/52° F	20°/10° C 68°/50° F	27°/11° C 81°/51° F	18°/04° C 65°/40° F	22°/07° C 72°/44° F
2/19/96	29°/19° C 84°/66° F	20°/11° C 68°/51° F	28°/10° C 83°/50° F	16°/06° C 60°/43° F	17°/04° C 62°/40° F
2/20/96	25°/14° C 76°/57° F	12°/07° C 54°/44° F	21°/13° C 70°/55° F	13°/06° C 55°/42° F	19°/07° C 66°/44° F
2/21/96	26°/11° C 78°/52° F	17°/06° C 62°/43° F	26°/12° C 78°/53° F	12°/00° C 53°/32° F	16°/-06° C* 61°/22° F*
2/22/96	23°/07° C 73°/44° F	13°/08° C 56°/46° F	21°/03° C 69°/38° F	10°/-06° C 50°/21° F	
2/23/96	23°/07° C 73°/44° F	19°/00° C 66°/32° F	25°/-01° C 76°/31° F	09°/-04° C 48°/25° F	

*Since localities other than the Racetrack were visited on February 21-23, the maximum/minimum temperatures for the cumulative three-day period is recorded without knowledge of when the extremes were collected.

Temperatures at the Racetrack were fairly comparable to those recorded at Scotty's Castle and at Wildrose, two locations at similar elevations. The conditions in Death Valley itself (Furnace Creek and Stovepipe Wells) were between 5°-10° C warmer, consistent with the normal adiabatic lapse rate for dry air, about -9.8°C for every 1000 m increase in elevation (Barry, 1992). Note that on at least one occasion, temperatures fell below the freezing mark at the Racetrack during that week.

Further measurements of infrared emissivity of the sky and the playa surface were recorded with an Everest IR thermometer, pointed at a 45° angle due north, and then at the playa surface to calculate the thermal balance of the area (see Appendix E). Readings were taken at 15-minute intervals during daylight hours on February 18 and 19, 1996. Although temperatures were above freezing through that period (Table 4.1, page 84) the significant net radiation differential was indicative of the possibility of ice formation at night.

A handheld anemometer was used to record wind speeds; wind direction was measured with a compass. Since permanent instrumentation and long-term data logging was not permitted due to the area's wilderness status, wind velocities were recorded manually every 15 minutes. The map (Figure 4.2) suggests that air is funneled onto the Racetrack from the south and, if the patterns observed during this field survey are typical, the winds are most intense in the vicinity of convergence. Appendix E shows the complete results of the wind study.

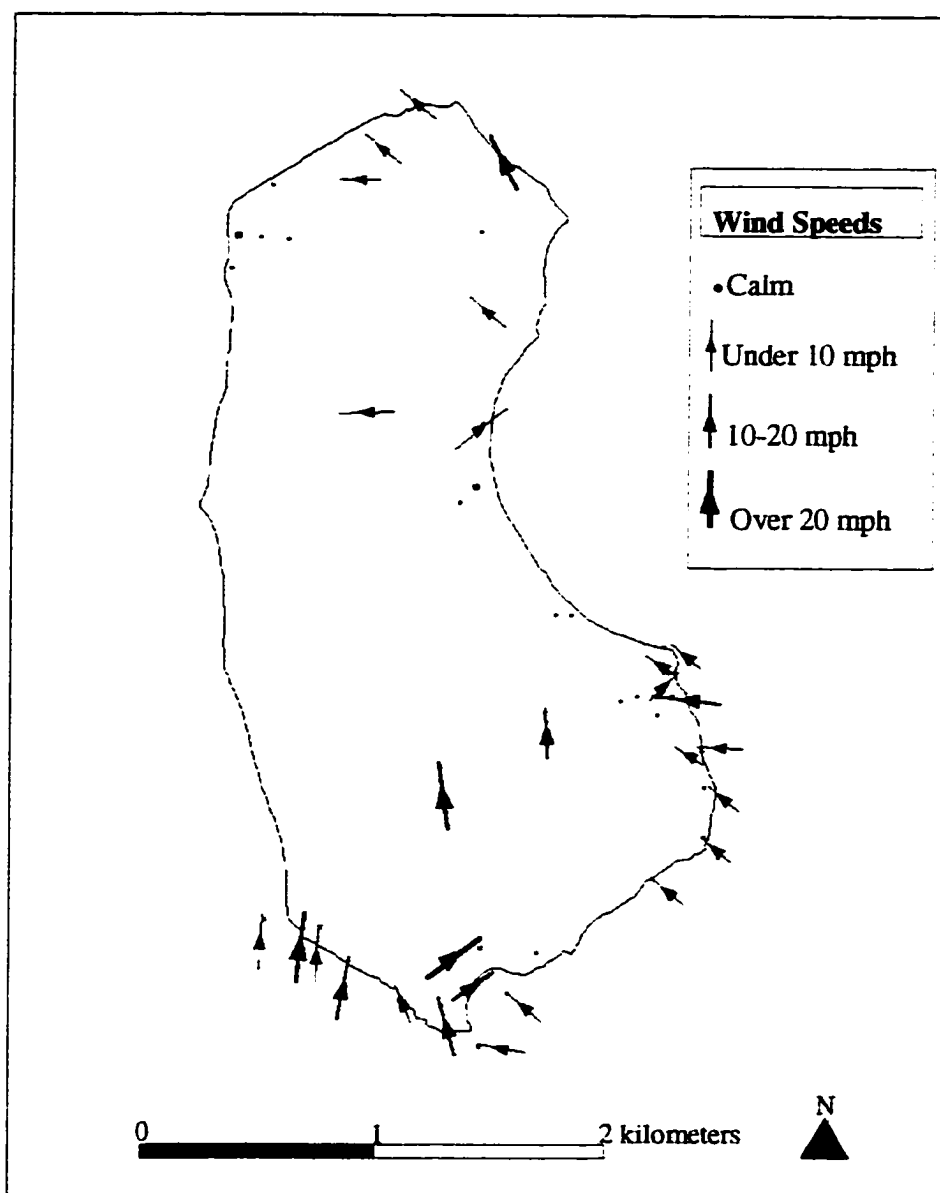


Figure 4.2: Wind directions and relative speeds on the Racetrack, February 18-19, 1996 (see also Figure 4.1, page 83). Note that these readings were *not* taken contemporaneously, so conditions changed with time as well as with location. Winds seem to be focused onto the playa from the south end.

4.2.2 Surface Deposit Characteristics

The playa surface was found to be a fairly uniform mosaic of desiccation polygons in February 1996, with a few notable exceptions. As was described by previous investigations (Stanley, 1955; Sharp and Carey, 1976; Reid et al., 1995) and by first-hand data collected during this field survey, the playa surface is indeed subject to freezing conditions. This can be inferred by the formation of ice crystal molds in some of the less-disturbed areas (Figure 4.3). Figure 4.4 shows the typical hard-baked surface that may not have been subject to local freezing, or where ice-induced features were not preserved.

Mud curls that form above the siltier layers composing the desiccation polygons are generally deflated by wind. These features, which have been called “cornflakes” by Robert P. Sharp, and “Special K” by this author are fairly uniform in size when eroded. The chips are carried to the playa perimeter where they tend to accumulate, especially around the base of existing vegetation barriers (Figure 4.5)

Shoreline characteristics indicated a previous flood condition in the form of a wrack line (Figure 4.6). Wave-carried sediments formed a faint line defining the geographic limits of a former pond. These features were most obvious at the eastern margins of the playa.

4.2.3 Hydrologic Features

Perhaps the most significant discovery made during the February 1996 scouting mission was the presence of three depressions in the easternmost quadrant of the playa. These crater-like pits ranged in size from under 1 meter to over 6 meters in diameter. Surrounding these depressions were significant “haloes,” of smooth sediment deposits in



Figure 4.3: A cracked portion of the playa surface showing ice crystal molds. Photograph was taken on February 18, 1996. Penny for scale.



Figure 4.4: The desiccation polygons of the Racetrack Playa are typically 5 - 10 cm. along any axis. Note the distinctive uppermost crust of mud curls (as described by Sharp and Carey, 1976) formed from the finest clay fraction, the last to settle out of standing water. Swiss army knife for scale.

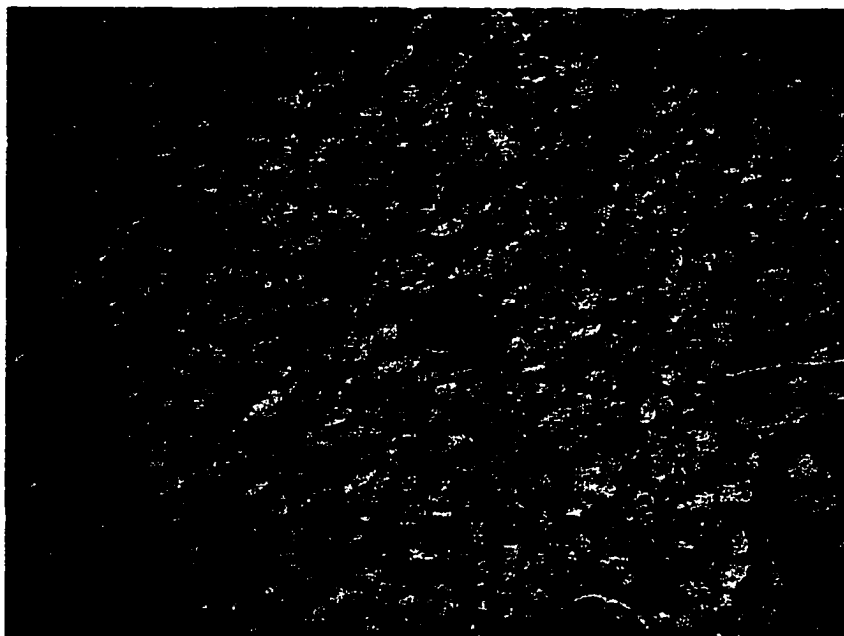


Figure 4.5: These deflated mud curls were photographed on the eastern playa boundary in February, 1996. Produced when the finest clay-rich film dries after a significant accumulation of rain, the chips are carried by the wind to the encroaching alluvial fans. Twenty-five cent coin for scale.



Figure 4.6: Wrack line showing wave features of ponding water at the eastern boundary of the Racetrack. Ubehebe Peak appears in the distance to the west.

sharp contrast to the desiccation cracks common on the rest of the surface. These rings, measuring 6-, 50- and 80-meters in diameter may indicate the extent of water accumulations, or they may indicate “gas ring” features, as described by Mabbutt (1977).

The largest depression had deeply incised dendritic channels leading into it from the south, indicating that water probably drains into these holes with relative force. It had significant ice crystal features at its bottom, suggesting that water had filled the depression and had frozen, possibly some time that winter.

The presence of these features was a surprise since they had not been described previously. Shelton (1953) described “man made depressions,” and Creutz (1962) discussed two sinkholes at the *southern* end of the Racetrack (see “2.8 Creutz, 1962” on page 38), but the three depressions observed were at the *eastern* boundary (see Figure 4.7); no such features were in evidence in the southern section at all. The depressions are reminiscent of solution holes as documented on Clayton Playa, Nevada by Motts (1965). However, the relatively-low salt content of the Racetrack, as evidenced by the surface structure of hard-baked contraction polygons (Mabbutt, 1977) seems to preclude the existence of significant subterranean evaporite lenses. The craters instead bear a striking resemblance to springs found on other playas in the area, one notable example on Big Smoky Playa, Nevada as described by Walker and Motts (1970) as an artesian feature. The USGS 7.5-minute Ubehebe Peak topographic map shows neither evidence of these depressions, nor the presence of any springs in the area. National Park Service rangers’ knowledge of these features was limited, although they had heard that the pits were dug out by ranchers as watering holes when driving cattle northward across the Racetrack from Hunter Mountain to Goldfield Nevada (Dan Dellings, personal communication).

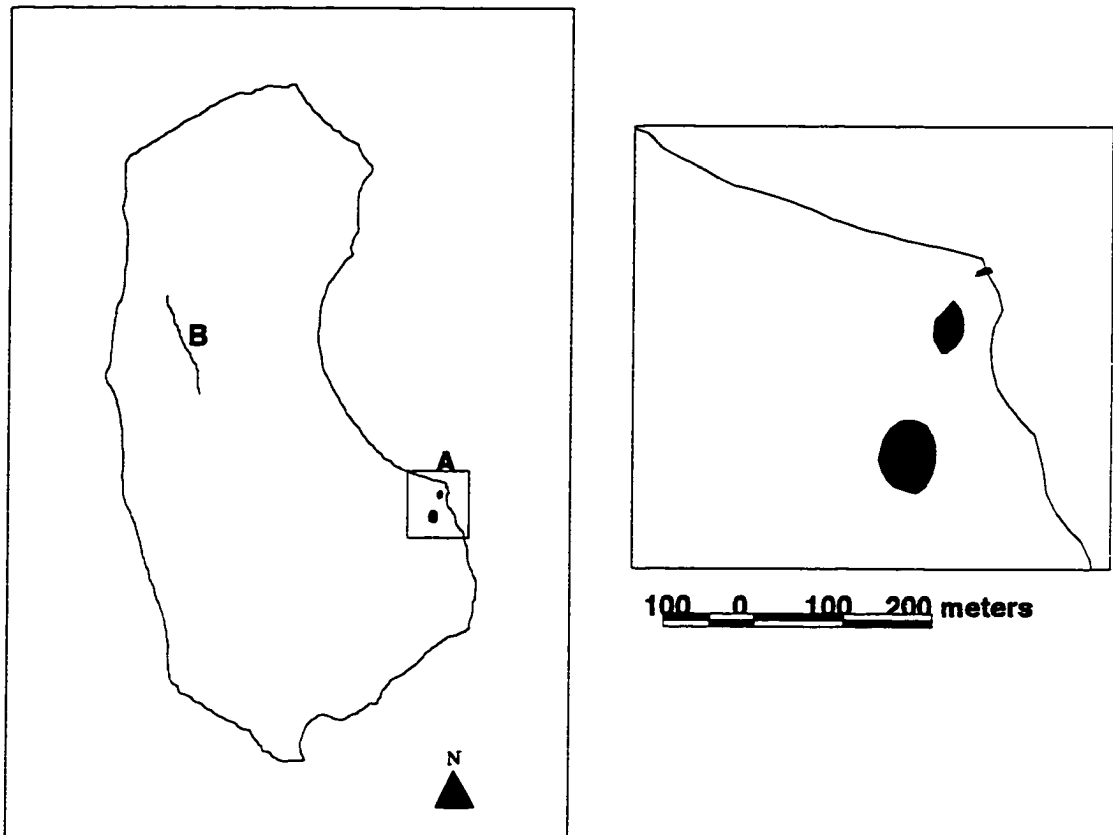


Figure 4.7: Outline map of the Racetrack Playa (left) shows the location of three depressions (inset A, right). The circular areas, as shown, indicate the limits of the smoothed playa deposits, suggesting the maximum recent extent of water, or surficial gas rings. The line marked B is a water seep, several hundred meters in length, where phreatophyte bushes have taken root.

4.2.4 Surface Scars and Clay Mounds

With the exception of the sliding rock features (which are described in section 4.2.5 and Chapter 5), the most impressive anomalies on the otherwise uniform playa crust was the presence of large expanses of darker, mud-curlled veneers forming irregular-shaped tracts. In some places, these finger-like extensions form nearly orthogonal stripes on the surface (see Figure 7.1, page 196).

The leading edges of these fine-grained deposits can be as much as several centimeters higher than the undisturbed surface beyond (Figure 4.8). The farthest limits of



Figure 4.8: Disruptions in the playa surface, these lobate mounds of very fine clays are possibly formed when glutinous, turbid water is propelled by the wind.

these peculiarities are sometimes angular, but more commonly sinuous in nature, suggesting origins due to fluid motion (Figure 4.9). When water is in contact with clays for a long time, the clays are transformed into a semi-liquid state (Motts, 1970); such a viscous mixture may be the key to these extensive accumulations.

The scars are possibly caused by the propulsion of turbid water sheets as observed by Bradley (1963). Stanley (1955) reported on prospector Joseph Crook's earlier observations of accumulations of water being shifted to different parts of the playa depending



Figure 4.9: Darker patches show areas where mud curls have not yet been deflated, indicating recent localized saturation. Notice the serpentine nature of the “bulldozing front,” implying that these finger-like projections may be caused by advancing mud-laden fluids, probably propelled by wind.

on the driving force of the wind. Sharp and Carey (1976) described an observation by Ranger D.W. Carney as a 2-centimeter thick water sheet advanced across the Racetrack; the event was accompanied by a sizzling noise, purportedly as air bubbled out of the dry deposits underneath. It therefore follows that as the water sheet is propelled, it transports silt and clay in suspension, later depositing them when calming conditions allow the smallest sediments to precipitate. Reid et al. (1995), however, interpret these mounds as ice-shove features. It seems possible that the more angular, abrupt subset may indeed owe its origin to the work of ice blocks scraping the uppermost saturated muds while sliding under the influence of strong winds. However, the majority of these features appear more fluid in form.

4.2.5 Sliding Rock Phenomena, February 1996

While the actual mapping project was not scheduled until July, significant attention was paid to the sliding rocks on the Racetrack in February. Photographs and field notes recorded some of the more unusual occurrences. There seemed to be no clear pattern to the nature of the trails, other than the general observation that most rocks appeared to move a few degrees east of north. While Sharp and Carey (1976) noted that the more angular rocks tended to produce straighter paths, this was not in evidence in February. For example, the rock shown in Figure 1.8 (page 15) is rather rounded, yet it produced a relatively straight trail. Figures 4.10 and 4.11 show dolomite boulders, typically blocky due to joint-controlled cleavage patterns, with curving, and markedly angular scars tracing their routes. By no means is a sample of three necessarily indicative of general trends, yet in retrospect these initial observations served as harbingers for the results of detailed analyses to follow.

The source material for the majority of rocks on the playa emanated from two steep abutments at the south end. These cliff faces are composed of fractured Racetrack Dolomite that apparently breaks and tumbles under a number of mass-wasting processes. Talus covers the playa muds at the foot of each slope. This otherwise uniform talus blanket is broken in some places by linear clearings (see Figure 4.12). Based on the continuous nature of these bare scars, they are most likely places where rocks started sliding. Had rocks tumbled the barren areas would have been spotty.

Many trails at the southern end of the playa appeared to be congruent, implying unison motion as noted by Stanley (1955) and Reid et al. (1995) (see Figure 4.13). However, upon careful examination of these parallel traces there were several examples that

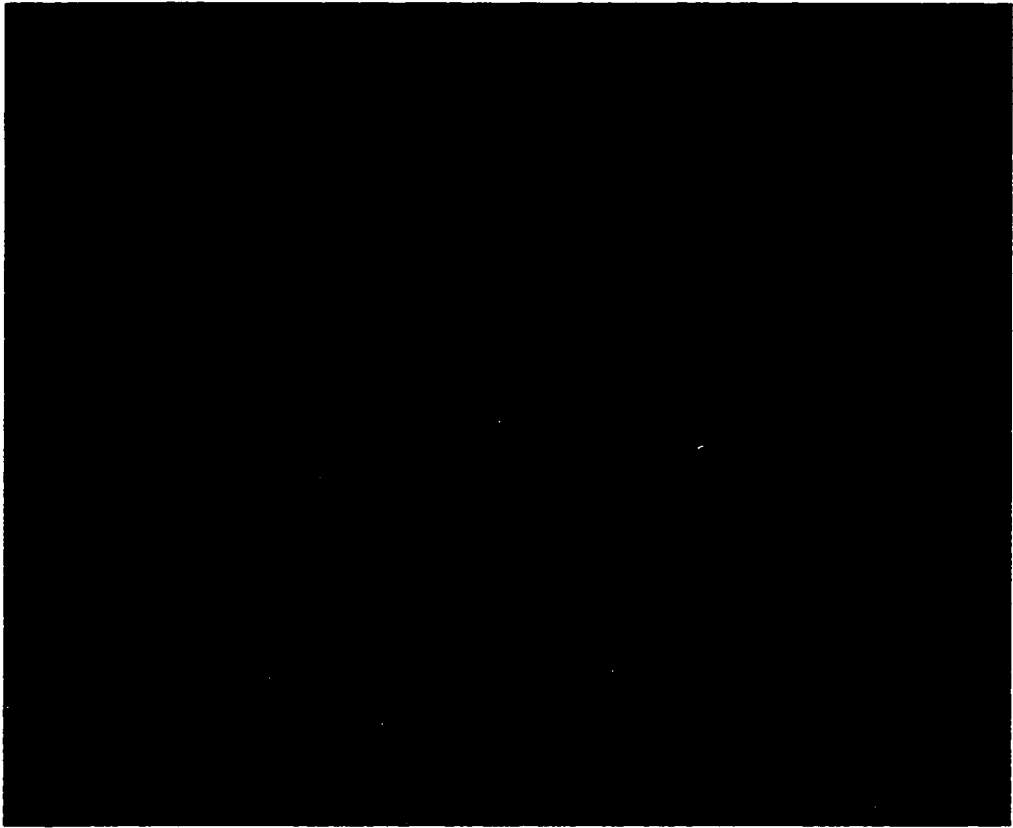


Figure 4.10: This blocky dolomite boulder produced a sinuous trail. Although headed in one general direction, the rock's path indicated a regular swaying motion as well.

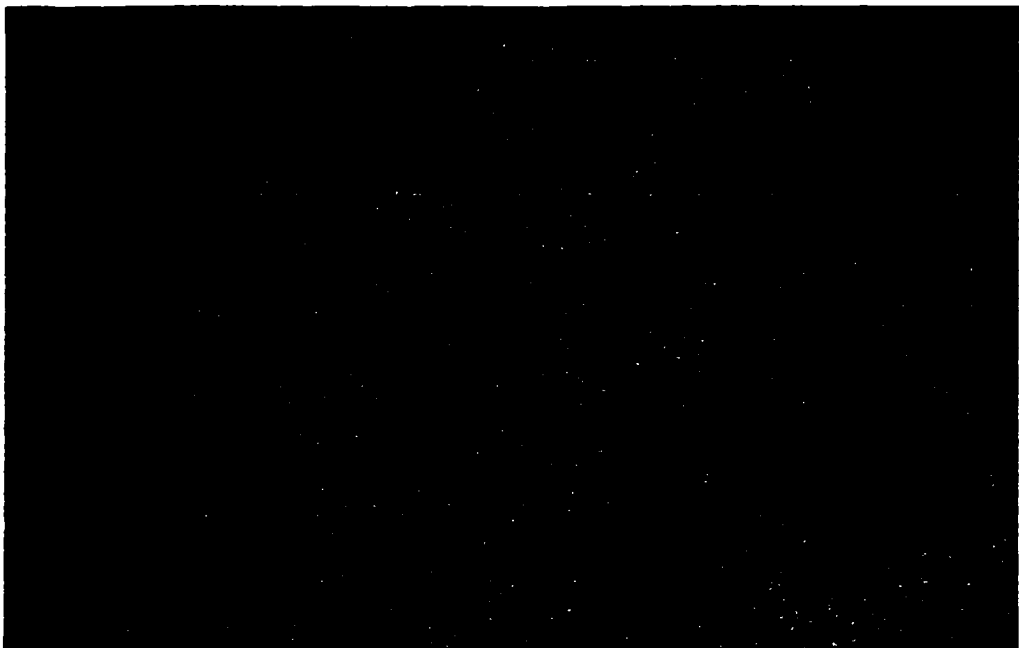


Figure 4.11: An angular dolomite cobble, and its angular trail. Note the smaller cobble in the distance, which has no trail associated with it.

thinned and widened, suggesting rotation during a sliding episode. If the pivots were coincident with turns in the trail, then the parallelism *could* be explained as the result of rocks' entrainment in a rigid ice sheet. Yet this was not always the case: trail widths sometimes varied independently of headings.

4.3 Field Studies of Other Mojave Playas

Clements (1952) sought to investigate sliding rock activity on playas other than the Racetrack (see page 22), and his motivating question was indeed logical: Why *isn't* this phenomenon more common? Rocks may skate across many dry lakes, but the accessibil-

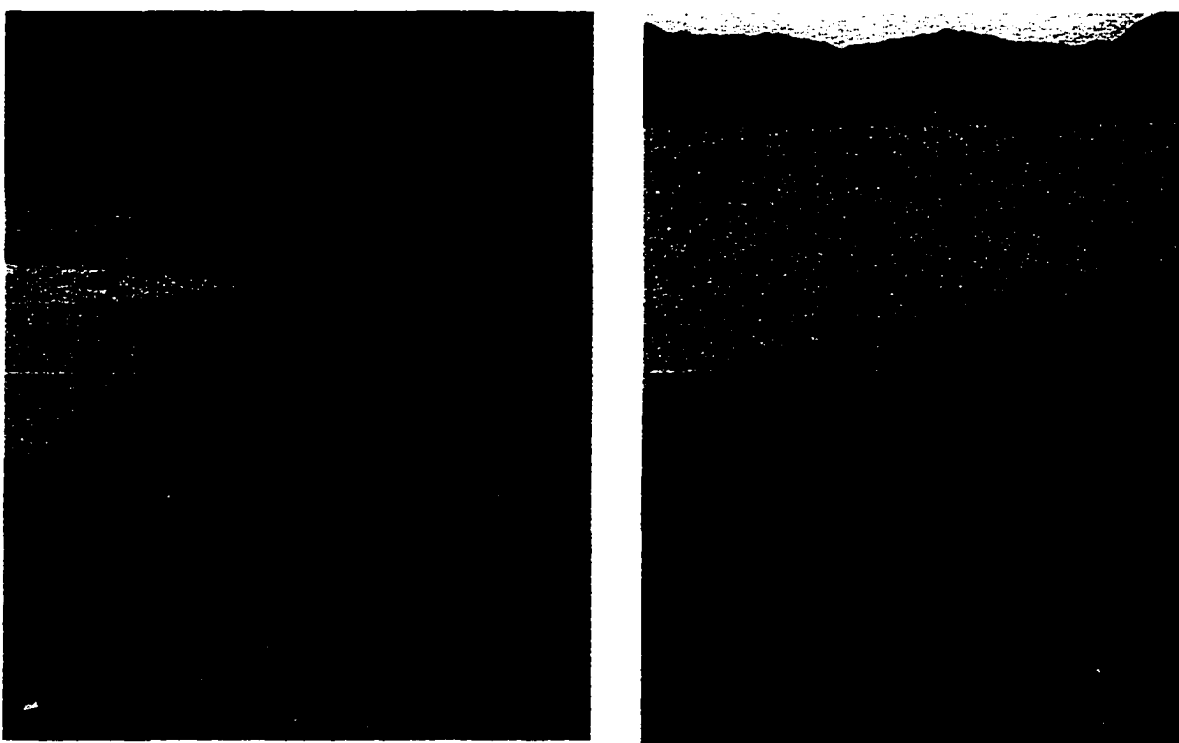


Figure 4.12: South end of the Racetrack abuts two steep bedrock walls, the apparent source area for most of the sliding rocks. A carpet of pebbles lines the interface. The image on the right shows a very faint “launch site,” a place where a rock bulldozed through the talus blanket, and then continued to slide along the mud surface producing a trail.

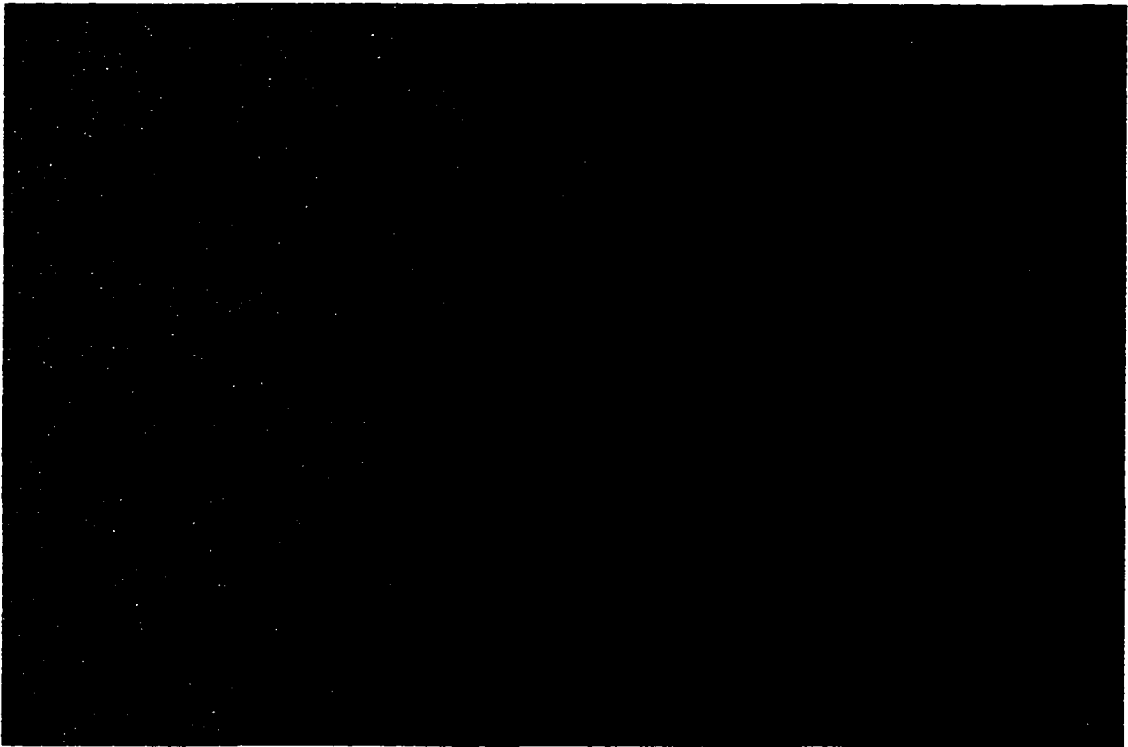


Figure 4.13: A high degree of parallelism in trails near the southern dolomite cliff walls may suggest the formation of a single roving ice sheet as the mechanism for rock motion. This photograph was taken from a vantage point on the western dolomite “rock nursery,” at a height of about 10 meters above the playa surface.

ity and preservation of the evidence may not be as keen as on the Racetrack. Motts (1970) stated “I believe that the movement of gravel and other materials across playa surfaces is probably a more prevalent phenomena [*sic*] than has been previously recognized because of the exacting conditions needed to preserve scraper trails.” Sharp and Carey (1976) enumerated reports of the process on several other Southwest playas (Table 4.2)

Table 4.2: Playas in Southeastern California and Adjacent Nevada Displaying Stone Tracks (Sharp and Carey, 1976)

Playa		USGS 7.5-Minute Quad(s)	Location		Elevation (meters/feet)
			Lat.	Long.	
Racetrack	CA	Ubehebe Peak	36°41'N	117°34'W	1131/3708
Little Bonnie Claire	NV	Bonnie Claire NW	37°10'N	117°10'W	1225/4016
Nelson Dry Lake	NV	Boulder City, SW Boulder City, NW	35°51'N	114°57'W	521/1708
Rogers	CA	Rogers Lake, N Rogers Lake, S	34°55'N	117°47'W	692/2269
Rosamond	CA	Rosamond Lake	34°50'N	118°05'W	693/2273
North Panamint	CA	Panamint Spgs., Nova Canyon, The Dunes	36°20'N	117°23'W	470/1541
Drinkwater	CA	Drinkwater Lake, East of Leach Lake	35°30'N	116°33'W	1022/3350
Small playa, Edwards AFB	CA	Rogers Lake, S	34°53'N	117°46'W	~693/~2271
Unnamed playa, north of Afton	CA	Dunn	35°05'N	116°26'W	570/1870

Motts (1970) reported finding numerous trails up to several hundred feet in length caused by rocks, pieces of iron and fragments of bushes on Rogers, Rosamond and North Panamint playas in 1967-68. Clements (1952) observed similar features on Little Bonnie Claire. But since documentation of these other localities is limited, it seemed worthwhile to visit the areas for a firsthand look.

Since Rogers, Rosamond and "small playa" are within the bounds of Edwards Air Force Base, and Drinkwater Lake is within the Fort Irwin military establishment those localities could not be studied without special permission. However, the others (Little

Bonnie Claire, Nelson, North Panamint and “unnamed playa north of Afton”) are on public land; all except for North Panamint, which lies within Death Valley National Park, are under the jurisdiction of the Bureau of Land Management. Between February and December 1996, all of these sites were visited on at least one occasion for examination of surface phenomena and evaluation of surrounding landscapes.

4.3.1 Little Bonnie Claire Playa

Little Bonnie Claire lies approximately 75 kilometers northeast of the Racetrack Basin at a comparable altitude in western Nevada (see Figure 2.3, page 23). Figure 4.14 shows a view of Bonnie Claire from the southwest. A visit in February 1996 revealed some interesting similarities to conditions observed at the Racetrack a few days earlier.

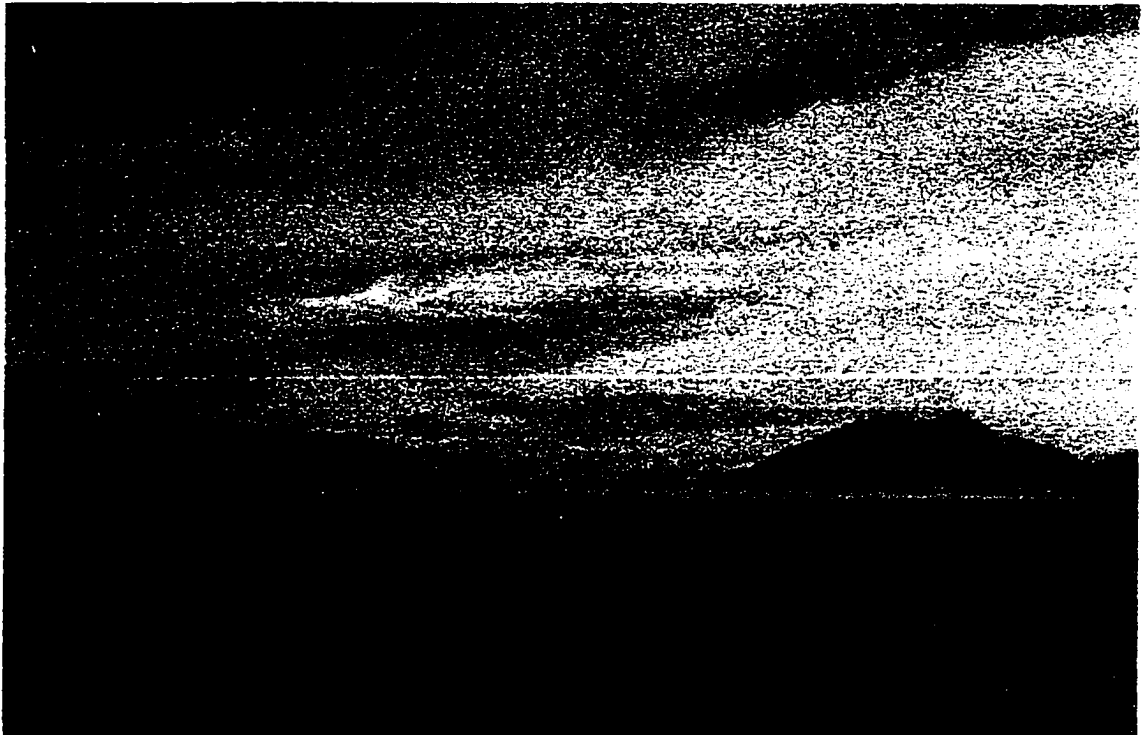


Figure 4.14: Little Bonnie Claire Playa is located on a plain constricted by mountains that rise to the north (left) and south (right).

When approaching Bonnie Claire from Nevada State Road 267 one is aware of an analogous topographic setting, with low mountains rising on two sides (Figures 4.14, 4.15). The major axis of the playa runs parallel to the two mountain fronts. The northern scarp abuts the playa, and is composed of volcanic scoria: the apparent source area of most rocks littering the lakebed's surface.

A few turn-offs lead from the road directly onto the playa floor; driving is permitted on Bonnie Claire. As a direct consequence, the area has been impacted by visitors whose refuse and abandoned campsites are prevalent. Any scraper trails were nearly impossible to discern from tire tracks, with the exception of one (Figure 4.16) which still had a rock in place at its terminus. The highly vesicular texture of scoria fragments makes them exceedingly rough and far more irregular in shape than the vast majority of rocks found on the Racetrack. A scoria cobble would be far more resistant to movement by traction due to its high-friction nature, but its decreased total contact-area with the playa surface may counteract this trait.

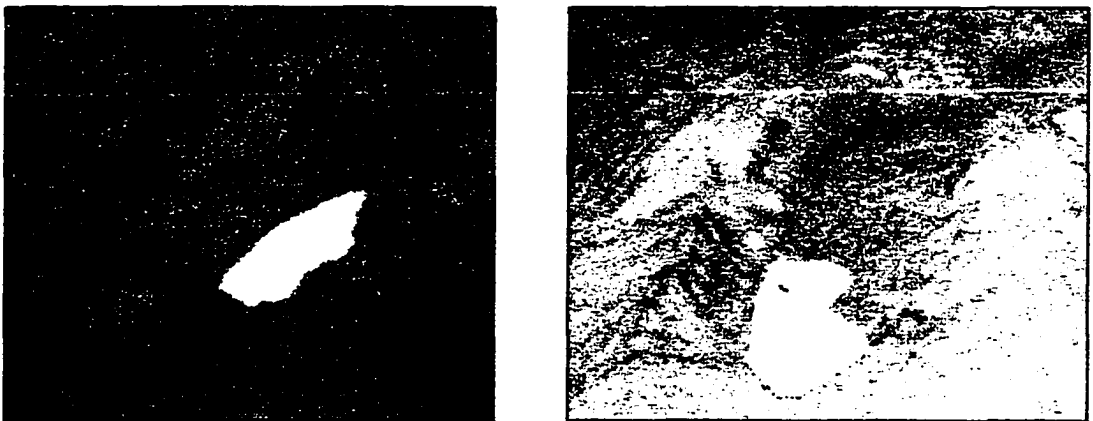


Figure 4.15: Two details of a scaled physical model of Death Valley and the surrounding area. Shown on the left is an oblique view of Bonnie Claire Playa, Nevada, looking southeast; the right image shows an oblique view of Racetrack Playa, looking north. Notice the similarities of the topographic configuration surrounding each dry lake. The model is on display at the Death Valley Museum at Furnace Creek.

Similar sloughs of the presumed water-mud mixture that produce the curvilinear mud mounds on Racetrack were located (Figure 4.17). Orientations of these elongated deposits were parallel to the major axis of the basin, indicating that prevailing winds are generally from the southwest.

The entire perimeter of Bonnie Claire was investigated by car. Near its southwestern limits were several dozen pebble-sized rock fragments, each resting in relatively smooth dry muds. Emanating from the points where rocks were set there were chevron-shaped discolorations in the mud, suggesting that water flowed past these deposits. The rocks seemed to act as obstacles to the current, recording their interference in the clays.

Perhaps the most distinctive surface feature on Bonnie Claire was a “mud volcano” near its northern shore (Figure 4.18). This mound of clay, complete with a central crater, is clearly the result of the artesian eruption of groundwater.

There are several free-flowing springs in the Death Valley area, some of which (in Saline Valley) are hydrothermal in nature. The production of the Saline Valley hot springs

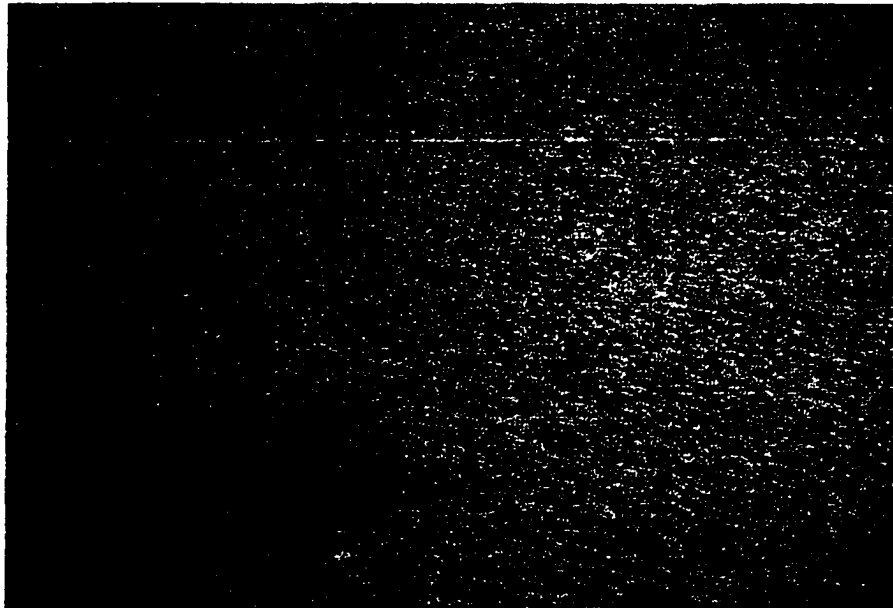


Figure 4.16: Cobble-sized rock, showing a faint trailing furrow on Bonnie Claire Playa, February 19, 1996.

are seismically influenced. As an active rift belt it is possible that Death Valley area springs are controlled by geotectonic activity, and this may be true for the groundwater features on Bonnie Claire and Racetrack. However, a search of recent earthquake activity shows surprisingly little seismicity for the Death Valley region. Other nearby springs, such as those found in Ash Meadows National Wildlife Refuge in western Nevada, are fed by underground aquifers. The subterranean waters originate as subaerial drainage of the expansive Amargosa Valley, later percolating into the basin floor and resurfacing where the topography and water table intersect.

The source of water for the outlets on the playas is probably meteoric, perhaps falling locally as precipitation on the mountains surrounding the basins, or farther away.



Figure 4.17: A mud mound heads a superficial scar on Bonnie Claire Playa, similar to the sliding mud deposits on Racetrack (Figures 4.8, page 92; 4.9, page 93; 7.1 page 196). The two parallel features that cross the scar are tire tracks.



Figure 4.18: This mud volcano was photographed on Bonnie Claire Playa on February 19, 1996, and its continued presence was confirmed in August of the same year. This feature is most certainly the result of the hydraulic head of subsurface groundwater, occasionally punching through the nearly-impervious muds.

4.3.2 North Panamint Playa

The north-south striking fault graben that parallels Death Valley to its west is the Panamint Basin, home of two dry lakebeds. Sliding rock activity was reported by Motts (1970) on North Panamint Playa, which is pictured in Figure 1.5 (page 12). The dry lake surface is the physical equivalent to those of Racetrack and Bonnie Claire, indicating compositional similarities. Desiccation polygons form a continuous hard floor in the valley.

Visits to North Panamint Lake in February, July and December 1996 revealed no sliding rock trails. Having been incorporated into the national park in 1994 when the boundaries were expanded, Panamint Valley used to be a haven for off road vehicle enthusiasts. The tire-scarred surface is only now beginning to heal. Any pre-1994 sliding rock

activity would be difficult to confirm, since anthropogenic trails (i.e., those of motorbikes, all-terrain and off-road vehicles) are common and difficult to distinguish from naturally-formed furrows. A plenitude of rocks exist on the playa, some several kilometers away from possible source areas. Yet most rocks appeared to have been embedded into the playa surface when it was softened, and lie sunken as much as several centimeters deep. This is a sharp contrast to the nature of the surficial rocks of Racetrack and Bonnie Claire.

North Panamint Lake lies in the center of a very broad (over 10 kilometers wide) basin, with gentle bajadas forming transitional slopes between the plains and the steep mountain fronts. At its eastern margin is Lake Hill, a basaltic mass that clearly serves as the source for the pebbles and cobbles found on the playa floor. This rock type contains relatively few gas bubbles, and fragments are therefore much smoother than the scorias on Bonnie Claire. While there are many such volcanic rocks on North Panamint, none showed evidence of sliding to its current location.

The visits to Panamint did reveal several geomorphic analogs to the Racetrack. The playa crust sloughs off into “Special K” fragments that accumulate around the roots of bushes. There are numerous crater-like depressions on Panamint’s surface, remarkably similar in nature to the three described on the Racetrack (Figure 4.19). A complete count was not attempted, but it is estimated that their numbers exceed one hundred. It is likely that since these features are indistinguishable from those on the Racetrack, they are caused by similar processes. The folk tale used to explain the Racetrack features as “watering holes” adds a bit of romance to their origins, but probably little truth.

The craters on Panamint Playa were dry in February 1996, but contained differing levels of water on subsequent visits; the same was true for their Racetrack counterparts

(see “4.5.2 Hydrologic Features” on page 123). Since 1996 was a relatively dry year in Death Valley (total annual rainfall registered under 3.5 centimeters at Furnace Creek), it makes little sense that these pools would contain water if their only sources were directly meteoric. Panamint Valley is at an elevation of 470 meters; this fact, compounded with its position in the rain shadow of the Sierra Nevada Mountains result in high temperatures and low precipitation rates year-round.

When viewing the valley from atop Lake Hill, one can detect linear ditches fragmenting the otherwise continuous playa floor. Paralleling these cracks are lines of bushes that apparently benefit from the occasional water that accumulates in them. Whether this network is due to contraction of the clays, or to subsurface jointing is unknown. Along

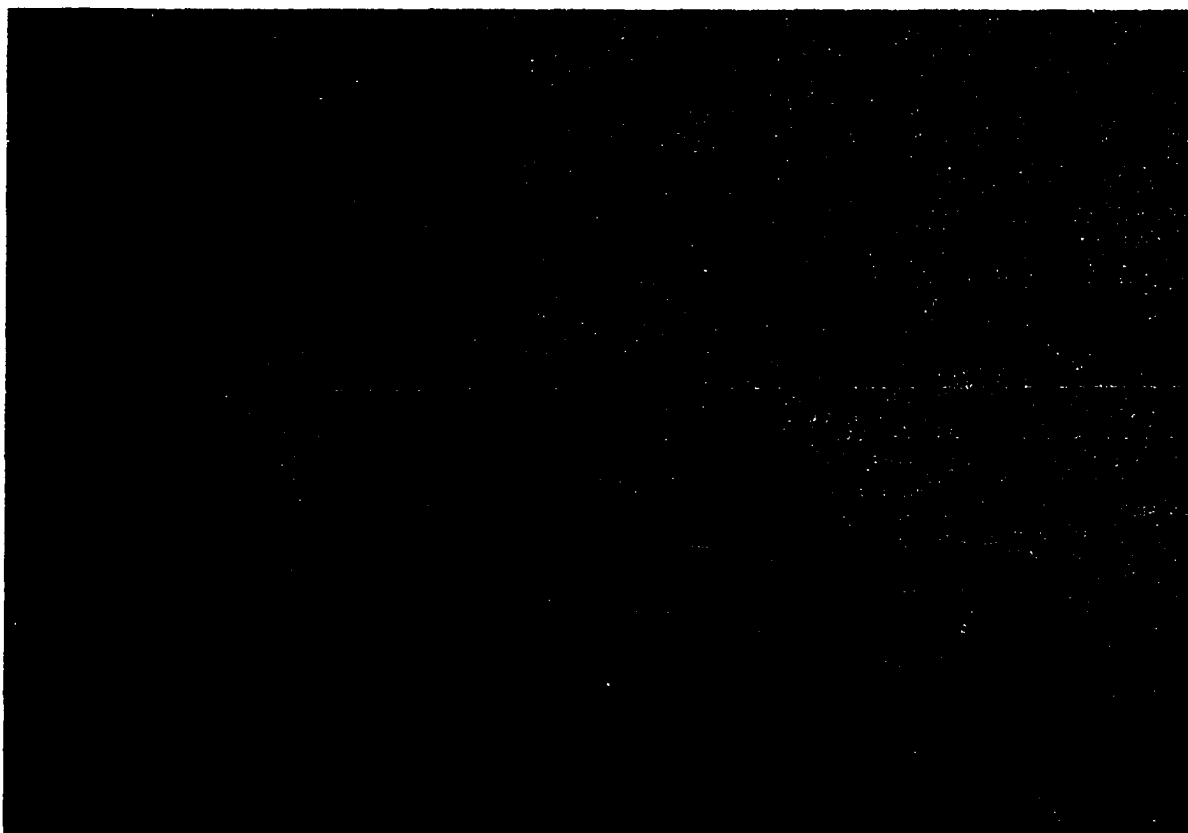


Figure 4.19: Two depressions on North Panamint Playa. These craters are identical in morphology to those found on the Racetrack, although these two examples are smaller. Field notebook for scale.

with the associated “parasitic” vegetation, Panamint’s surface is therefore distinctive from the Racetrack’s unbroken and flat expanse.

4.3.3 Other Playas

Nelson Dry Lake, recognized as a sliding rock locality by Stanley (1955), was visited in August 1996. It lies southwest of Boulder City, Nevada along US Highway 95. As BLM (Bureau of Land Management) land, driving is permitted and there are several ramps that lead from the highway directly onto its surface. As with other under-protected places, there was ample evidence of human activity in the form of broken beer bottles, tire tracks, fire rings, even an abandoned washing machine. There were no sliding rock trails apparent, but there were several boulders on the flats. Analogous depressions to those found on Racetrack and North Panamint dotted the otherwise continuous, mudcracked surface. The depressions held no water in August 1996.

Nelson Dry Lake was noted a few years earlier, on an unrelated trip to southern Nevada. Driving south on highway 95, a massive windstorm intensified in the area until a dust devil was spotted rising several hundred meters into the sky. As the vortex wandered around the dry lake it twisted the fine-grained sediments high into the air. Visibility decreased and vehicles subsequently pulled off the highway. Drivers waited along the sides of the road until much of the activity diminished. Witnessing such an event was alarming yet providential. Although a short-lived incident (the local conditions improved in under 10 minutes), it was dramatic and violent. Had it taken place when the playa was wet, it would have seemed reasonable to expect larger materials to move around the slickened surface.

The only other accessible sliding rock locality as recounted by Sharp and Carey

(1976) (see Table 4.2, page 98) was a “small unnamed playa north of Afton.” On a December 1996 trip, equipped with a handheld GPS receiver, the coordinates of the unnamed lake and the USGS 7.5-minute Dunn CA quadrangle, the vicinity of the purported feature was scouted by automobile. Despite its proximity to Interstate 15, a route to the playa was not apparent. The USGS map shows a mining operation on the dry lake, so it is possible that any natural features that may have existed in the past have since been obliterated. Sharp and Carey (1976) report that sliding rock trails were observed by Lyle Hoag, but particulars are nonexistent since it was based on unpublished data.

Having visited several Mojave playas, it was clear that the Racetrack offered the best-preserved instances of sliding rock phenomena, and so emphasis was placed on this locality over all others.

4.4 Racetrack Mapping Project, July 1996

This research project required an accurate map of the entire rock and trail inventory on the Racetrack Playa in context of the surrounding terrain. While transits and theodolites provided previous researchers with sufficient capabilities, a more complete and broader-scope survey was necessary for this study.

4.4.1 Preliminary Concerns

Previous researchers’ results showed single-episode trails up to several hundred meters in length. Having conducted preliminary field observations in February, the need to trace several kilometers of trails was anticipated. If standard surveying instruments were used, the maximum mapping range would have been 300 meters using 3-meter stadia rods. Some trails would certainly necessitate relocating the equipment at least once. Each

move would have required a great deal of time and effort: every set-up (i.e., levelling and sinking the tripod, levelling the instrument, backsighting, etc.) could be accomplished in no less than several minutes. Considering the extreme heat and aridity on the playa and the need to leave no semi-permanent scars on its surface, a more time-efficient and less-intrusive method of mapping needed to be considered.

Sub-meter accuracy was essential to producing a detailed map of the sliding rock trails. The map would have to be completed by a field crew of only two with limited funding, in a restricted time frame (i.e., under one month). These requirements alone made Differential Global Positioning System methods the only reasonable choice for this mapping project.

Researching the specifications of different manufacturers' instruments to suit the project's needs was the first step undertaken. Given the rapid rate of change of this technology-driven industry, the Internet seemed like the only resource that could provide up-to-the-minute information. Several educational and government websites provided background information on the theory and uses of DGPS technology, while commercial GPS manufacturers' home pages showed comparisons of available equipment.

With limited financial resources it was possible only to rent a GPS receiver for the duration of the project; purchasing equipment capable of sub-meter resolution was cost prohibitive. Further Internet searching provided comparative pricing and leasing information.

Cost was only one consideration when deciding to abandon hopes for real-time differential corrections while mapping, as none of the USGS benchmarks indicated on the Ubehebe Peak topographic map could be found during the February visit. By default, the

field work collected data that included the 100-meter Selective Availability drift which was later corrected when base station files were downloaded. A base station in Sacramento was used since its files were stored with compatible software, and the limited baseline (about 400 kilometers) ensured that the same satellites as were above the horizon in Death Valley were continually in view from that location. Using this configuration, the estimated resolution of the final product would prove to be about 30 centimeters (see “5.2 Spatial Resolution Analysis” on page 128).

4.4.2 Data Collection Considerations

Equipment included a Trimble 8 channel C/A code Pro-XL receiver and TDC1 data logger. Connected to the GPS rover was an antenna and extension arm affixed to a back pack; powering the receiver were two VCR batteries, allowing for eight hours of data capture between recharges. The TDC1 was loaded with Asset Surveyor software which interfaced with a laptop computer’s Trimble Pathfinder software via a parallel port cable. Data uploads from the laptop to the data logger were necessary before mapping could commence. A “data dictionary,” a database adapted for this specific project, needed to be designed and saved using the Pathfinder program, and then uploaded to the data logger. The data dictionary is similar to a blank accountant’s ledger, with the necessary number of columns and self-assigned categories. Knowing which geographic information system (GIS) application would be utilized after post-processing was important even at this early stage due to differences in individual package’s database management capabilities. For example, the data dictionary designed for this project was configured to store separate point, line, and area templates for eventual conversion to ESRI ArcView “shape file” format; had Arc/Info been planned for later use all three types of data could have been stored

in the same coverage. It should be noted however that transformations between formats were possible, and indeed were conducted during the data analysis stage (see Chapter 6).

The rover was programmed so that data collection would automatically pause whenever the satellite geometry resulted in Position Dilution of Precision (PDOP) values over 6.0. Luckily, on the Racetrack, satellite configurations provided excellent data collection conditions in the early morning (i.e., PDOP readings were generally below 3.0, which is considered an optimum situation), conveniently when it was coolest. Some disintegration occurred early in the afternoon, when temperatures coincidentally soared, making field work dangerous anyway. When a PDOP over 6.0 was calculated, the TDC1 would audibly warn its user, and pause. This would signal the surveyor to stop, and if in the midst of collecting line or polygon features, wait until satellite geometry improved. Sometimes this would take only a few minutes and mapping could resume without too long an interruption. In the early afternoon, however, PDOPs would maintain values over 6.0 for longer periods, making mapping virtually impossible. Hence, early afternoon became a time to download data, annotate field notes, eat lunch or head back to Stovepipe Wells.

A vertical mask of 15° was set for data collection; this resulted in selective reception of satellite signals 15° or greater in altitude. Since the Racetrack is surrounded by ranges, it is unlikely that satellites closer to the horizon would be detectable anyway, yet setting this mask provided insurance that the base station, 400 kilometers away, was obtaining data from the same SVs in the limited cone above Death Valley. Differential corrections would be impossible if the base station and rover were not concurrently obtaining transmissions from the same satellites.

Default settings on the GPS unit captured data in decimal degrees, and were referenced to the World Geodetic System of 1984 (WGS 84). Decimal degrees were converted to UTM coordinates by the Pathfinder software after downloads to the laptop computer.

The project began on July 17, 1996 when, at 3:30 AM, this author and a field assistant left Stovepipe Wells Village in Death Valley for the two-hour road trip (spanning just over 100 kilometers), to the Racetrack Basin. When approaching the playa the first rays of sun had just begun to illuminate the highest reaches of Ubehebe Peak. By the time the car was parked and the equipment readied, light flooded the valley. Beginning this early in the day was mandatory due to the dangerous ambient temperatures encountered in the afternoon.

As in February, a minimum-maximum thermometer was established in a sun shelter where it was monitored and reset daily. The temperature data for the duration of the mapping project appears in Table 4.3.

Table 4.3: Air temperatures in Death Valley National Park, July 1996

Date	Minimum/Maximum Temperatures				
	Furnace Creek EL-55m/-180 ft	Scotty's Castle EL 914 m/ 3000 ft	Stovepipe Wells EL. 0 m/0 ft	Wildrose EL. 1312 m/ 4000 ft	Racetrack Playa EL. 1131 m/ 3708 ft
7/17/96	45°/30° C 113°/86° F	36°/21° C 96°/70° F	44°/26° C 110°/79° F	34°/15° C 93°/58° F	38°/21° C 99°/70° F
7/18/96	48°/28° C 117°/82° F	37°/21° C 98°/70° F	46°/28° C 114°/82° F	35°/15° C 95°/58° F	39°/19° C 102°/66° F
7/19/96	48°/27° C 117°/81° F	39°/24° C 101°/75° F	47°/29° C 116°/83° F	36°/19° C 96°/66° F	40°/20° C 104°/69° F
7/20/96	49°/30° C 120°/85° F	40°/25° C 104°/76° F	48°/28° C 118°/82° F	38°/20° C 100°/68° F	41°/22° C 106°/71° F
7/21/96	51°/33° C 123°/91° F	41°/27° C 106°/80° F	50°/32° C 121°/89° F	39°/22° C 101°/71° F	43°/22° C 108°/72° F
7/22/96	*	*	*	*	43°/19° C 108°/66° F
7/23/96	*	*	*	*	43°/26° C 108°/78° F

*Official NPS weather data for 7/22 and 7/23 were not available

4.4.3 Points, Lines and Areas

The plan was to record the positions of all rocks on the playa (points), to trace all sliding rock trails (lines), and to demarcate the boundaries of significant landforms such as the Racetrack and Grandstand perimeters (areas). The TDC1 was programmed to record each point feature as a 10 spot-fix average: while holding the antenna stationary over each rock, points were sampled every second for 10 seconds. When 10 points were recorded, the TDC1 signalled that the point feature had been captured. Later graphic displays of

these samples showed the slow and gradual S/A drift, and other errors. In a 10-second span, however the maximum X-Y difference between any two points sampled was in the centimeter range.

Lines representing sliding rock trails were mapped by walking their extents with the surveyor acting as a “human digitizer.” An effort was made to capture only single-episode trails; the ends of trails (where the rocks rested) were most clearly defined, but in some instances a path seemed to emanate as a more diffuse trace. In these cases, only the more conspicuous part of the trail was logged. Some routes showed intermediate “sitz marks,” described by Sharp and Carey (1976) as depressions within a trail indicating a resting spot for its associated rock. It was often difficult to determine whether a trail extension was carved *minutes* or *years* before the formation of a sitz mark, hence the determination of a “single event” of motion was somewhat subjective.

The paths were traced from the terminus (where the rock rested) to the origin with the equipment idle. Once at the tail-end, mapping would begin as the surveyor walked back to the rock, sampling vertices every two seconds. While it may seem redundant to have walked each trail at least twice, tracing the trails *in the direction of motion* was essential for later analyses (see Chapter 5). When back at the terminus, a high-contrast (painted) pebble was placed on the sliding rock to indicate to the field crew that it had already been recorded. Information including the rock’s lithology, height, width and length were recorded digitally (stored in the GPS data files), by a digital camera and manually in a field notebook.

But before any of the details were mapped, the Racetrack perimeter and other significant boundaries were recorded. The largest polygon, the Racetrack, was sampled at a

rate of one point every 10 seconds. Selecting this rate somewhat diminished resolution, but decreased the ultimate size of the digital file. The boundary of the playa is somewhat diffuse in places (Figure 4.20, page 115), especially where encroaching slopes spill coarser alluvium during flash floods. The western border is less ambiguous, though unnaturally so, bounded by the NPS-dug ditch, which contained several centimeters of water when the mapping project began (Figure 4.21, page 115).

Ultimately, the Racetrack outline was portrayed by 544 points, defining a perimeter of 12,000 meters, and encompassing an area of 680 hectares.

All hydrologic features were captured on the first day of field work. The western sinuous seep was recorded as a line 715 meters long, with 48 phreatophytes (point features) dotting its length. The depressions at the east end of the playa (see “4.2.3 Hydrologic Features” on page 87, and Figure 4.22, page 116) were filled with water, flooding out the lowest branches of the twenty bushes that usually surround their exteriors. The pools were teeming with brine shrimp. Coyote tracks in the softened muds indicated that local animals were aware of the existence of these reservoirs. The perimeters of the flooded areas were recorded as polygons and every salt bush specimen was recorded as a point.

4.4.4 Sliding Rock Data Capture

July 18, 1996 was the first day of mapping trails and rocks. Efforts concentrated on the western reaches of the playa, especially since Stanley (1955), and Sharp and Carey (1976) noted a preponderance of anomalous south-moving stones in those areas. While a few point rock locations were mapped, many had no trails. Conversely, there were some trails that had no rocks. This pattern did not persist in the eastern and southern quadrants,



Figure 4.20: Mapping the perimeter: the north and east sides of the Racetrack are bounded by encroaching alluvial fans, making its border diffuse. In the distance (right) are bushes that encircle one of the pools of water.



Figure 4.21: The western border is more distinct. After a rain one week earlier, the ditch that bounds the Racetrack contained standing water. The ditch is a source of controversy. Constructed to prevent vehicles from driving onto the playa, it also cuts off sediment supply from Ubehebe Peak and mountains to the west.



Figure 4.22: The depressions shown in the map of Figure 4.7 (page 91) were filled with water in July 1996. The pools are refuges for birds and other animals, as inferred by footprints left in the saturated mud, while macroscopic brine shrimp inhabit the turbid waters. Note the feral burro bones in the foreground.

and it was attributed to vandalism. It is no coincidence that these areas are in close proximity to the only access road.

Rocks were assigned consecutive numbers beginning with 1; dimensions were recorded electronically and manually after measuring height (vertical extent), length (maximum horizontal dimension) and width with a metric measuring tape. On each successive day, additional rocks and trails were numbered and mapped, measured, imaged and described in field notes (see Appendix F).

Concurrent to the GPS data collection, digital images of the rocks were gathered.

A measuring rod painted with 10 centimeter high-contrast segments was placed next to each rock, pointing north, for scale and orientation in the images. The digital camera contained a 1-Megabyte memory chip, permitting storage of about 16 JPEG-format files. When more than 16 rocks were mapped in any one mapping session, images would have to be downloaded mid-day (Figure 4.23).

There were a total of seven rocks whose images were *not* saved, due to unknown causes. Those rocks were ultimately photographed with a 35 mm. camera in March 1997, so the photo library of all rocks was ultimately completed. Since the rocks could not be marked in any way (as per the National Park Service research permit), these images will provide their identification for any future monitoring activities.

After each day's field work, data files consisting of thousands of coordinates, some



Figure 4.23: Mid-day downloads were sometimes necessary, although mostly for image storage purposes. Note the Trimble Pro-XL leaning against the car. The Grandstand, the low dark knoll, is visible in the distance.

belonging to subsets of line features, some representing points, were downloaded into a laptop computer where Trimble's Pathfinder software was resident, allowing for limited screen display of the uncorrected features. Base station files could technically have been downloaded nightly, but phone lines in Death Valley were not capable of fast-speed data transfer via modem, so differential corrections had to wait until the mapping mission was finished.

On July 23, 1996 data collection was complete. As is visible in Appendix F (Figure F6) numerous and anomalously long trails, requiring tracing the greatest total distance, were recorded on the last day of field work. The task was difficult to accomplish, especially since it took place on one of the hottest days, with increasing humidity. All told, it is estimated that the two team members walked a cumulative total of 100 kilometers through the course of the survey.

July 23 was also the only day during the mapping project when any appreciable clouds formed. Thankfully, the 162nd (final) trail had already been mapped when an afternoon monsoon-type event developed. Instead of cooling the air, conditions only worsened as humidity climbed, lightning threatened and winds started to strengthen. In a matter of minutes, winds swept through the basin causing us to seek shelter inside our vehicle. Silt and larger particulates were carried high above the playa in a massive wind storm; several erratic dust devils were observable on the playa, stirring up the bone-dry hard pan as though it were surfaced with loose powder (Figure 4.24, page 119). It was clear that the extremely hazardous conditions would have caused a serious threat, had we not reached the car by then. The winds flushed the airborne particles up and over the ridge to the west which includes Ubehebe Peak.

This episode lasted only 15 minutes, but in that short time a substantial quantity of sediment was transported *through* and *thoroughly out of* the Racetrack Basin. As the earlier experience on Nelson Dry Lake (see “4.3.3 Other Playas” on page 106), this incident was impressive in both its intensity and brevity. Within minutes, conditions reverted to the calm that characterized the previous six days.

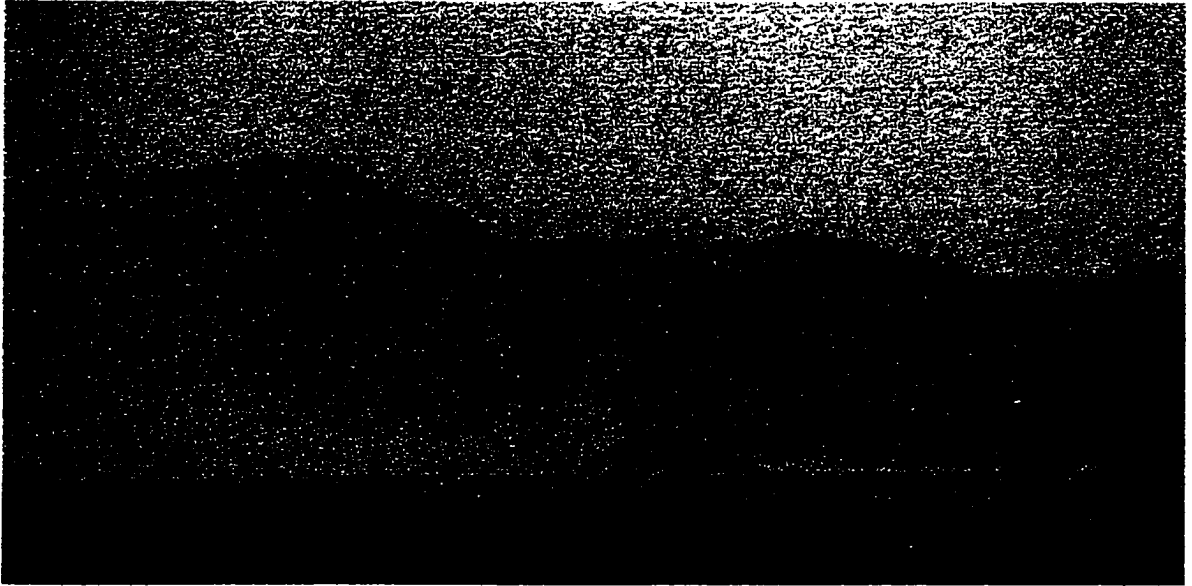


Figure 4.24: The Grandstand was almost totally obscured by rising plumes of playa sediment on the afternoon of July 23, 1996. Particulates were ultimately lifted over 600 meters high, up and over the western mountains and most likely into Saline Valley. Vortices snaked along the playa for several minutes before the event subsided.

4.4.5 Post-processing

With all data files downloaded from the TDC1 to the laptop's Pathfinder software, the equipment was returned and base station files were copied in Sacramento. Unfortunately and unknown to the survey team, the base station had gone down for a few hours on July 23. A sister receiver in Fresno provided the missing logs via modem. Trimble's utility, MCORR-400 designed for long baselines, was used to negate the effects of Selective

Availability and other atmosphere-caused errors.

Differential corrections brought the resolution of the final product to the desired sub-meter range. After the raw data files were corrected, they were exported to a variety of GIS formats, including ESRI ArcView shape files and ESRI Arc/Info coverages. A discussion of the final resolution, the results of GIS conversions and specifics of map construction are outlined in Chapter 5.

4.5 Racetrack Playa, Follow-up Visits

Return trips to the Racetrack Playa were made in December 1996 and March 1997. Descriptive field notes and illustrative digital images and photographs were taken, but no further mapping was conducted. A handheld GPS receiver permitted navigation to previously-mapped trails and it was determined by comparison of the surface features to the map generated in July that no detectable movement episodes had occurred in the subsequent months. This is not surprising since Death Valley experienced one of its driest years on record in 1996, and it had received only 0.1 centimeters of rain in the first three months of 1997.

4.5.1 Meteorological Survey, December 1996

The spot wind measurements recorded earlier in the year (see “4.2.1 Meteorological Data” on page 82) were followed up with a survey on December 26, 1996. Once again as stipulated by national park permit, only handheld instruments could be used for registering wind readings. Three field assistants equipped with identical Davis Instruments’ Turbometer anemometers and Silva compasses recorded wind velocities along parallel transects at the south end of the playa (Figure 4.24).

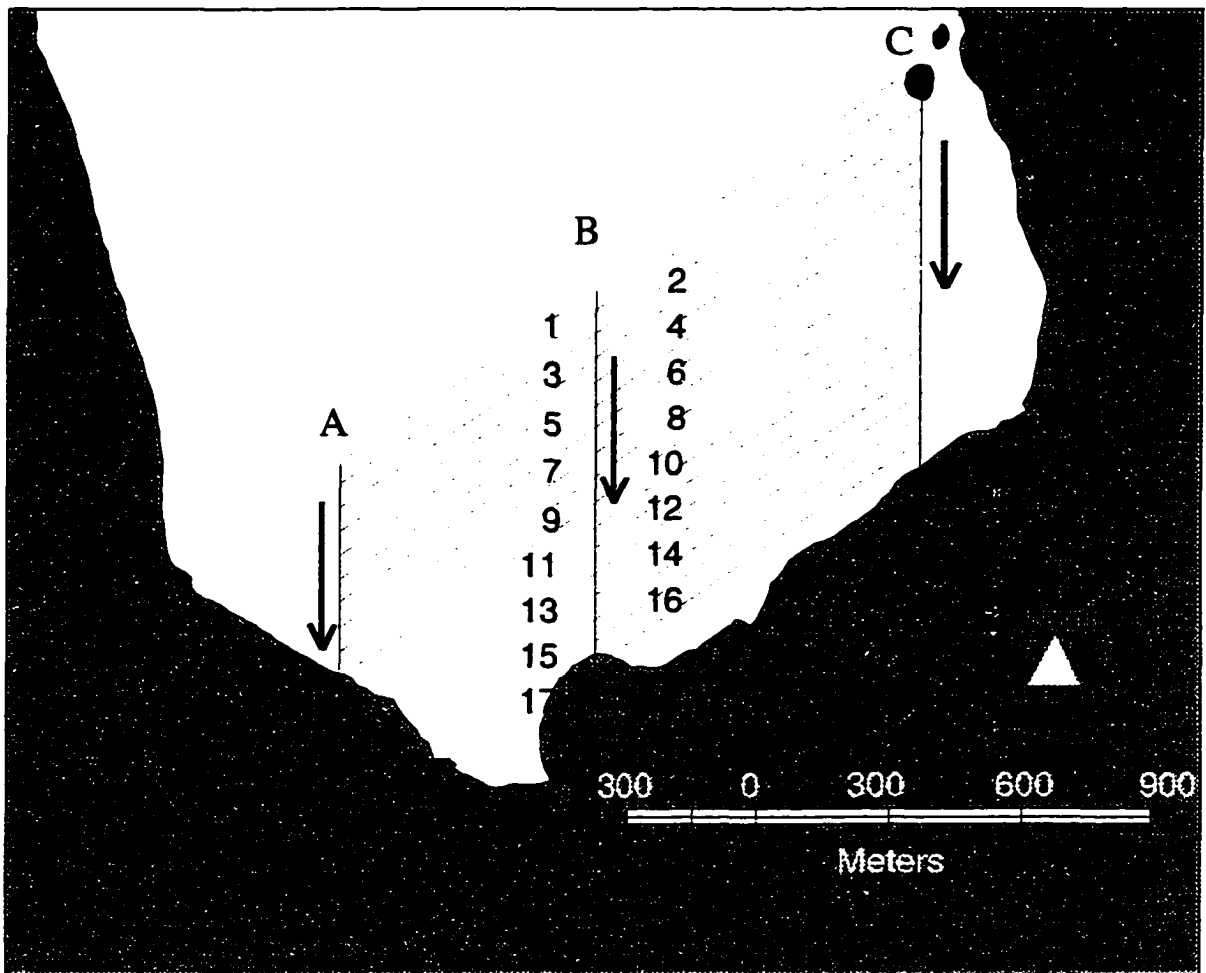


Figure 4.25: Wind velocities along parallel transects (dotted lines) of the south end of the playa were simultaneously monitored during one survey in December 1996. The letters “A,” “B,” and “C” are just north of the initial locations of three field assistants. Readings were taken every minute (starting with the transect labeled “1”) and progressed as the recorders walked due south until all three had reached the shore. Data follows in Table 4.4.

At the start, field surveyor “A” was stationed at a known point in the southwest sector of the playa, surveyor “C” at the southernmost spring, and surveyor “B” stood between the other two; a handheld GPS device recorded the spot fixes. When projected to the south, the three point locations bounded a polygon that encompassed the major boulder field. Watches were synchronized beforehand, and when all three recorders were at their assigned start points, wind direction and speed were measured at a 1 meter height above the playa surface. After recording the first spot measurement, the team walked due

south, guided by compass headings. The pacing speed of each member was roughly equivalent, as was assessed by earlier practice sessions. At the end of every minute, readings were taken and recorded until each member reached the shore.

Table 4.4: Wind Velocities at the South End of Racetrack Playa, Dec. 26, 1996

Stop	Time	A		B		C	
		Speed (mph)	Direction	Speed (mph)	Direction	Speed (mph)	Direction
1	1:13 pm	8.0	190°	13.1	180°	10.0	180°
2	1:14 pm	7.1	195°	9.6	180°	10.0	180°
3	1:15 pm	9.0	190°	14.2	180°	8.0	180°
4	1:16 pm	9.5	190°	13.5	180°	8.8	180°
5	1:17 pm	10.8	190°	14.5	180°	8.8	180°
6	1:18 pm	8.0	195°	13.9	180°	12.3	170°
7	1:19 pm	9.2	195°	14.7	180°	9.7	170°
8	1:20 pm	7.0	195°	13.1	180°	9.6	175°
9	1:21 pm	8.1	195°	15.2	180°	10.5	175°
10	1:22 pm	8.0	195°	15.4	180°	9.2	170°
11	1:23 pm	(no data recorded)		13.4	180°	5.9	170°
12	1:24 pm	5.0*	200°*	14.6	180°	6.0	170°
13	1:25 pm	4.6*	210°*	12.7	180°	4.8	170°
14	1:26 pm	5.3*	200°*	13.4	180°	12.0	190°
15	1:27 pm	3.5*	230°*	12.8	180°	12.0	200°
16	1:28 pm	2.0*	210°*	12.3	200°	11.1	230°
17	1:29 pm	Calm*		10.4	200°	9.8	220°

*These readings were taken at the south shore (the terminal point of line "A")

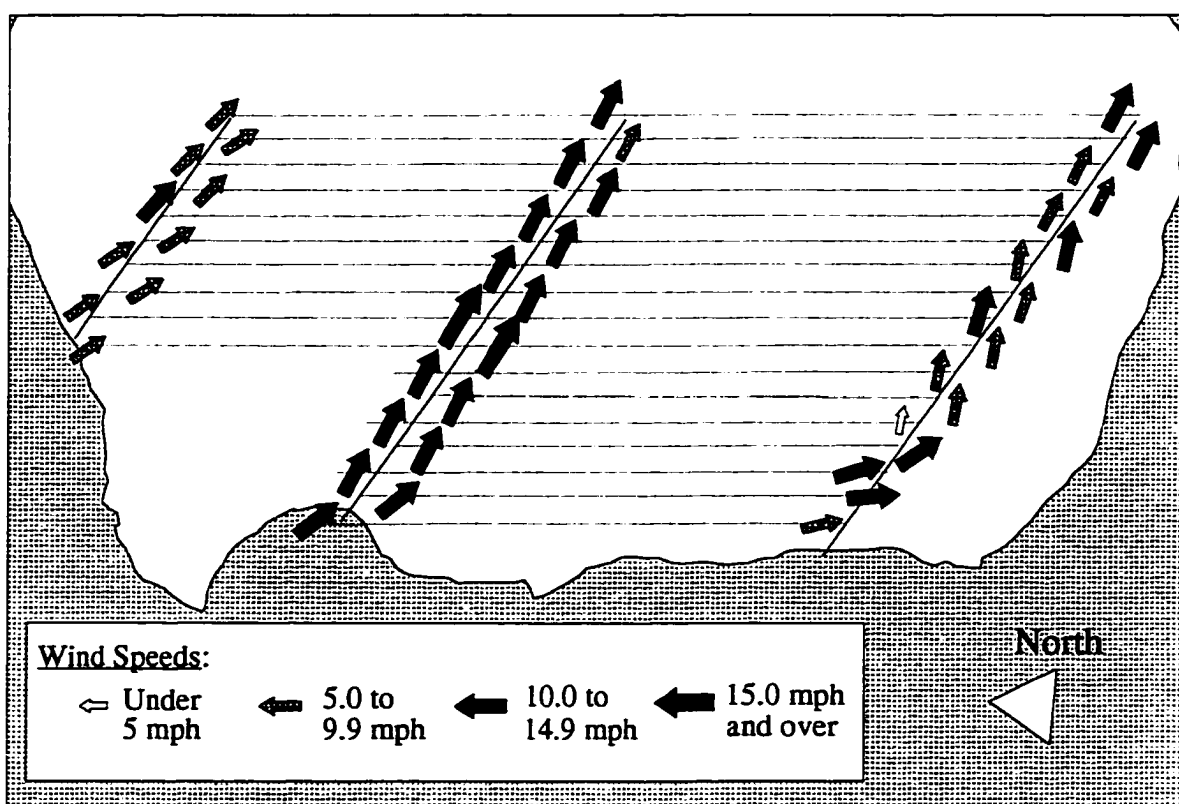


Figure 4.26: Graphic representation of winds observed on Racetrack Playa, December 26, 1996. Note that the greatest speeds were detected in the central part of the lakebed, and greatest variability in velocity is apparent at the eastern margin.

Figure 4.26 shows this data transposed onto a map. Note that the most intense winds were consistently observed in the central regions of the playa; calmer conditions persisted closer to the perimeter, typical of fluid flow. Air currents are most erratic in the east where wind direction and speed changed most frequently.

4.5.2 Hydrologic Features

The lack of rainfall in 1996 and early 1997 would have certainly resulted in the complete desiccation of the depressions on the Racetrack, but on both visits the pools were filled with water. In December 1996, the water in the largest pool was turbid and still. Observing carefully near the center of the pool one could see distinct currents of *clear* water upwelling from the bottom. This was the first time that direct evidence of a sub-sur-

face water source was noted in this area. Given the drought conditions throughout the Southwest, this demonstration confirmed what had been suggested by previous observations: the pools of water are natural springs.

Similar conditions existed on Panamint Playa during a visit a few days later. Some pools were filled, others contained a few centimeters of water while still others were dry. Surprisingly, there seemed to be no correlation between crater depth and water quantity. This suggests that the pits are not intersecting a shallow water table, and they are not collecting rain. These observations insinuate the role of subsurface fractures and joints, which may be channeling groundwater preferentially to some locations, and not others. Therefore, the possibility exists of a water source other than local rainfall adding to surface saturation of these playas.

Chapter 5

Data Analysis

With the digital data collection phase completed, attention turned to assimilating the sliding rock trail vectors into a geographic information system (GIS) for map composition and associated data analysis. Inputting the information to an automated platform allowed for examination of spatial and quantitative patterns; such analyses would have been virtually impossible had only paper maps been drafted. The data base capabilities of a GIS combined with its flexibility for customized display manipulations brought new techniques to this “old” problem.

The restrictions imposed by the National Park Service to preserve the Racetrack’s unique features are necessarily strict. The long-term monitoring arrangement conducted by Sharp and Carey (1976) could no longer be carried out under today’s heightened wilderness constraints. Therefore, the *only* future studies of the playa *will* be non-impact ones. As a baseline for future comparisons, the data are digital, generic, and adaptable to a variety of formats. Furthermore, the files themselves are compact, and easily transferred between systems.

5.1 Racetrack Playa Map Construction

Soon after the raw data were corrected, the files were converted to ESRI ArcView and ESRI Arc/Info formats. The transition was achieved by an export utility included in

Trimble's Pathfinder package. Some unresolved glitches in the Arc/Info utility resulted in files that required significant editing, however the ArcView shape files were successfully generated. The PC and UNIX versions of ESRI's ArcView 3.0 were therefore chosen as the GIS package for map construction. Practical benefits of using ArcView included its accessibility and its capacity to transfer data seamlessly between UNIX and PC platforms.

Shape files, ArcView's formats for vector data storage, were imported into the GIS. Separate files existed for rocks (points), trails (lines) and areas such as the Racetrack perimeter (polygons), as was dictated by the design of the data dictionary before field work began. Associated database entries for each of the feature records stored annotations such as rock number, dimensions, lithology, and other field notes.

Using ArcView, a georeferenced base map of California was added to an empty "view window." With the California polygon displayed, the GPS files were added as "themes" in the same view, with the projection set as Universal Transverse Mercator (UTM). Although at first, it seemed as though the files did not import properly since no added details were visible, this was simply a function of the initial map scale (it displayed the entire state of California). When the Racetrack perimeter theme was made active, ArcView's zoom function properly showed the outline of the Racetrack and every rock and trail mapped. The Racetrack appeared in precisely the correct location within California's boundary, and the same can be said for every rock and trail, within a small margin of error (see section "5.2 Spatial Resolution Analysis" on page 128). Adding annotation to the map completed the visual aspect of the project (Figure 5.1). The map was exported by ArcView into a compressed raster-format graphic file, later transferred via File Transfer Protocol (FTP) to Death Valley National Park. It was plotted there on poster-sized paper,

and a copy of it is stored at the Visitor Center.

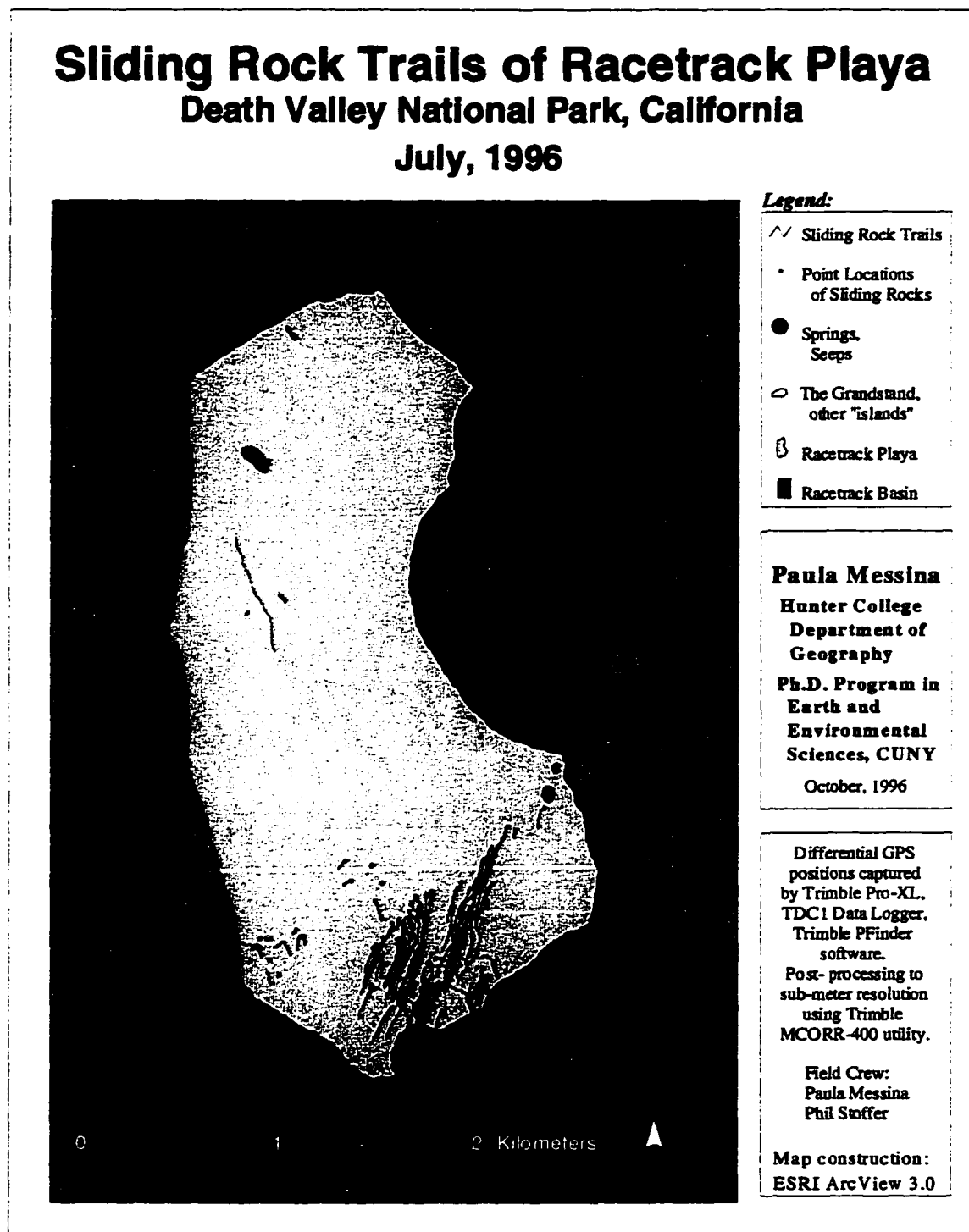


Figure 5.1: Complete trail map of sliding rocks of Racetrack Playa, July 1996.
 (Detailed, large-scale maps of individual trails are found in Appendix I.)

5.2 Spatial Resolution Analysis

During data processing minor spatial inaccuracies were noted; all of them were the results of expected, acceptable errors and were well within the range of sub-meter resolution. Figure 5.2 shows samples of the error which varied with data collection conditions; larger inaccuracies probably resulted from PDOP values approaching the limit of 6.0. The highest noted distance between a rock and trail was under 80 cm., but there were many instances of sub-decimeter values clustered on the final draft.

Figure 5.3 shows a trail that was inadvertently digitized twice. The two line features, captured about an hour apart, show a high degree of congruence. Yet upon close

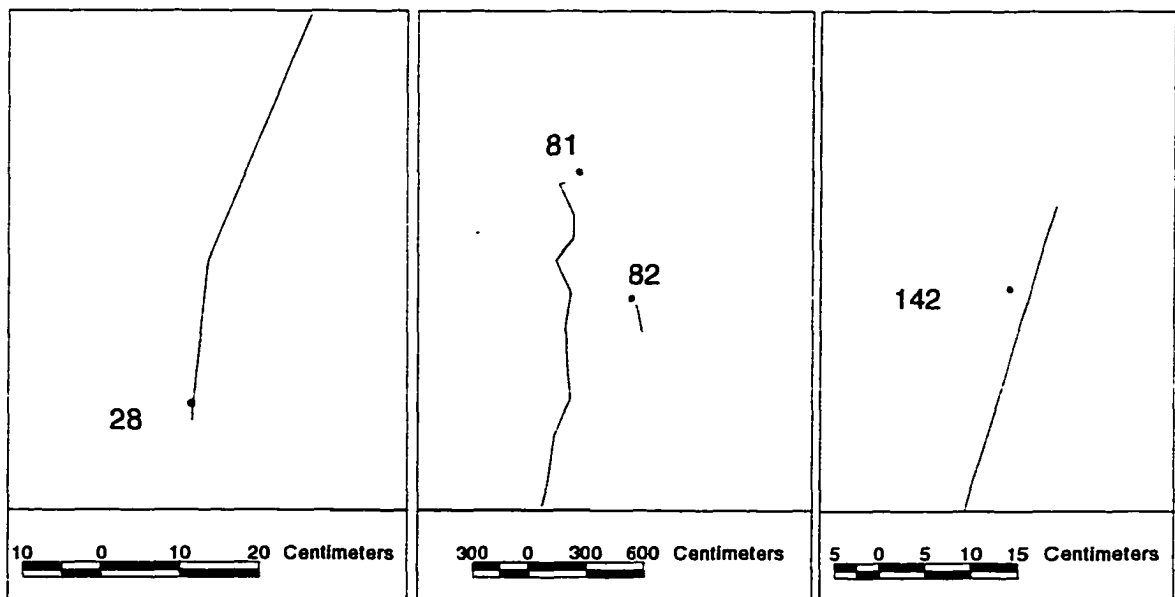


Figure 5.2: Sample instances of locational inaccuracies in the final map (Figure 5.1). Rocks, collected as separate entities, are shown as dots while their associated trails are displayed as lines. Each dot *should* be located at the end of a line, but, due to expected and unavoidable errors, this is not the case.

Beneath each map is a scale bar showing that errors varied from day to day; note also that the direction of drift is nonuniform. Rock #28 (logged on July 18) is shown 2.7 centimeters off its trail (left); rock #81 and rock #82 (both mapped on July 20) show gaps of 65.2 and 42.7 centimeters, respectively; rock 142 (captured on July 23) is shown 10.3 centimeters from the trail terminus.

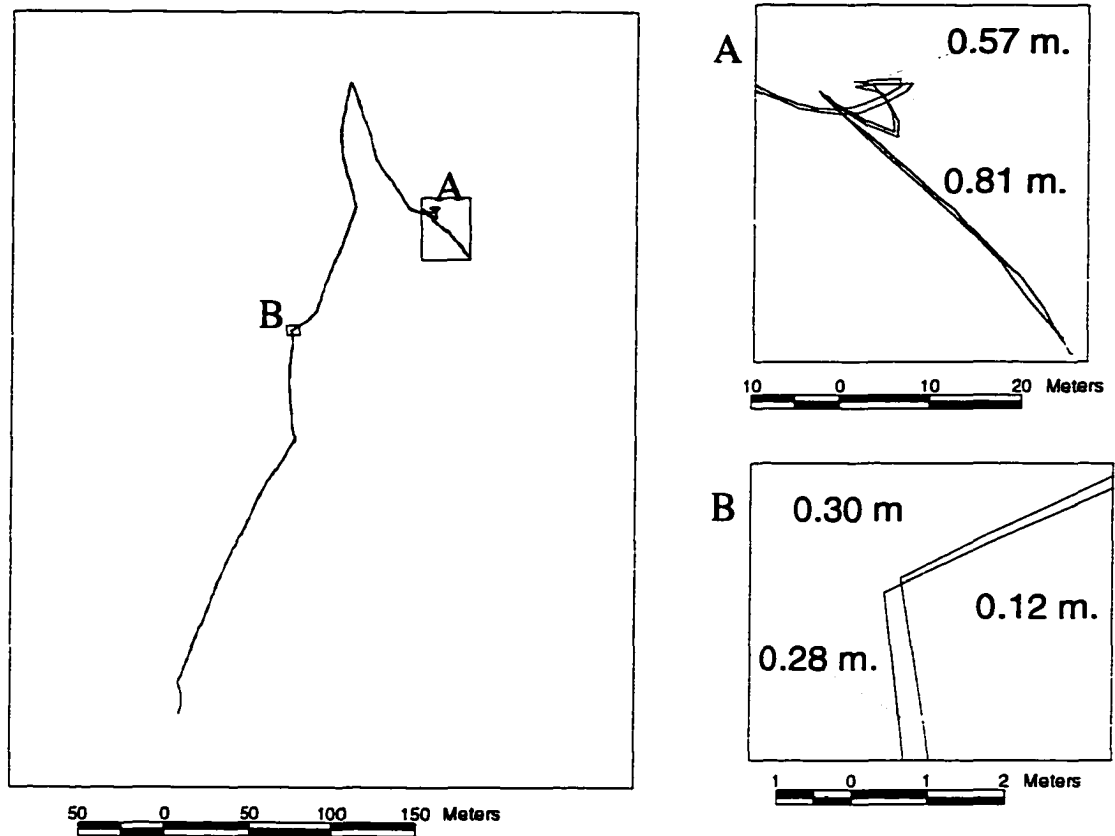


Figure 5.3: The trail belonging to rock #32 was digitized twice by mistake on July 19, 1996. Collected for the second time as rock #38, it was recognized as an already-mapped trail, but saved in the data set for later editing. When displaying the unedited file for that day's field work, both trails are fairly consistent. In this example, small errors (noted as the distances between vertices on opposing trails) could have been more significantly due to differences in the field workers' line-tracing precision than to digital data capture and processing errors.

examination, slight variations are evident.

Analysis of the map's components confirm that human errors are probably as significant as any caused by atmospheric disturbances, multipath problems, inadequacies in the differential corrections or other technological glitches. The GPS receiver's antenna was mounted on a backpack; it was the point continually defined by the GPS satellites and recorded by the data logger. Simple shifts of the surveyor's body weight or gait would change the position of the antenna leading to small discrepancies in the point and line features ultimately displayed on the map. Even if a local base station were used (thereby

maximizing ultimate resolution) these human errors would have persisted.

5.3 Data Sampling for Spatial and Frequency Distributions

The ArcView database files were converted to raw ASCII format and then imported into Microsoft Excel version 7.0. Once incorporated into an Excel table, the spreadsheet could be used for histogram generation, regression analyses and other statistical tests. It was decided to concentrate studies on the subset of rocks and trails at the south end of the playa, excluding the few samples mapped on July 18, 1996 (see Appendix F, Figure F1). The rationale for focusing on the southern sector is that the rocks found at the western margin of the Racetrack were probably placed there by visitors. Especially since the excavation of the ditch (see Figure 4.21, page 115) and proximity to the road, it is unlikely that rocks currently tumble off the slopes of Ubehebe Peak unaided onto the playa. This twenty-feature western subset possesses the highest degree of inferred vandalism of any locality sampled. For example, there were nine rocks without trails (numbers 2, 3, 4, 5, 10, 11, 12, 13 and 20) and two trails without any evidence of what formed them (numbers 15 and 19). These facts combined with the features' distance to the hub of sliding rock activity made their elimination from the data analysis phase justifiable.

Of the rocks contained in the main sliding rock field, a few are missing from the spread sheet for various reasons. Number 38 (Figure 5.3, page 129) and number 39 were digitized twice, as rocks 32 and 74, respectively, and later eliminated from the data set. Similarly, trail 136 was at first incompletely traced, but later saved again as 140. Rock numbers 65, 66, 71 and 76 produced no trails and could not be confirmed to be of natural origin. Trail 58, belonging to a rock that probably headed from southwest to northeast had

a cobble at its inferred origin. This rock, collected as number 67, was probably placed there by a visitor and ignored in later analyses. Finally, the point locations of two rocks, 98 and 149 were saved but their respective trail files were corrupted for unknown reasons. Therefore, there are a total of ten rocks and trails missing from the associated data tables referred to in this chapter. Of the 162 rocks and trails initially mapped, a subset of 132 of the total is included in these analyses.

5.3.1 Rock Classification

Among the fields initially generated by the GPS data dictionary were rock number, lithology, height, width and length. Using this information rocks surveyed in 1996 were compared to those monitored by Sharp and Carey twenty years earlier (Appendix C). It is believed that seventeen of the “original” sliders were recognized in this project, and they were thereafter referred to by the names by which they were originally known (see page 42). Since a fraction of the rocks mapped in this project had been “positively identified,” the other *numbered* specimens were assigned women’s names as well both for consistency, and as a tribute to the work done by the previous researchers. A column was added to the spreadsheet for “rock name.” Table G1 in Appendix G shows the data collected and derived from this survey.

Note that slight variations in measurements exist between correlated rocks in Appendix C (Sharp and Carey, 1976) and Table G1, Appendix G (this survey). Since all rocks are derived from desert weathering processes, they are typically angular. Irregularities in shape obscured definitive determination of rock axes (length, width), and prevented exact measurements. In some cases the rocks whose names were taken from Sharp and Carey (1976) may show dimensional variations between the two surveys. Without the lux-

ury of permanent identifying markers the recognition of these seventeen rocks as those of the earlier monitoring arrangement, though based on several parameters, is nonetheless conjectural.

It was apparent from the field investigations that dolomite fragments composed the majority of rocks on the playa floor. Figure 5.4 shows the relative percentages of rock types encountered. This distribution confirms the major contributing source areas as the two dolomite bluffs at the south end of the Racetrack.

Sliding Rocks by Lithology

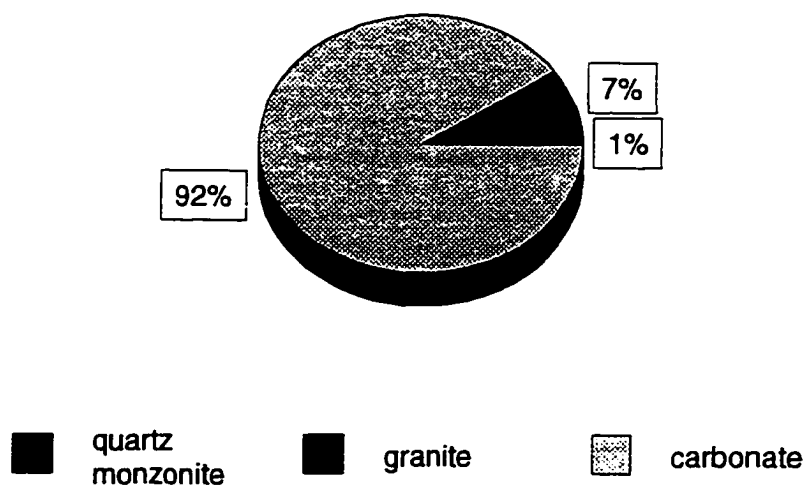


Figure 5.4: Sliding rocks, by lithology. Most rocks cleave off one of the two dolomite cliff faces at the southern border, as implied by this distribution.

5.3.2 Classification by Rock Size

As a stipulation of the National Park Service research permit, it was forbidden to move rocks in any way, even for measurement purposes; volume determination by water displacement or other invasive means was not allowed. However, rock height, length and width were measured in the field. A product of the three dimensions yields a “maximum volume” quantity that assumes a regular, rectangular shape. While most rocks did not fit this description, many (especially the carbonates) were naturally blocky, and therefore not substantially smaller than these overestimated values. The derived field in Table G1, Appendix G headed “>Maximum Volume” contains this calculated value. While it may not be highly precise for absolute volume determination, it may be used with confidence as a comparative descriptor. When categorized according to the modified Wentworth scale for clast size (Ingram, 1989), rocks sampled in this survey ranged from pebbles to boulders and followed a normal distribution (Figure 5.5).

The smallest rock associated with a trail (135, “Hanna”) had a bounding volume of only 150 cm³ and was categorized as a “very coarse pebble.” The largest clast size encountered, “medium boulders,” was comprised of a subset of three rocks: 45 “Karen,” 74 “Angel” and “94 “Kitty” with estimated volumes of 137,088, 168,750 and 199,500 cm³, respectively. The mean particle size was 14,113 cm³, indicating that the average sliding rock is a “large cobble.”

Spatial distribution of rock fragments shows that the boulders are more concentrated in the playa’s central region, north of the dolomite cliffs (Figure 5.6). This area contains a nonuniform assemblage of rock sizes. Sliding rocks closer to the eastern margin are more homogeneous in size class.

Frequency Distribution of Sliding Rocks by Volume

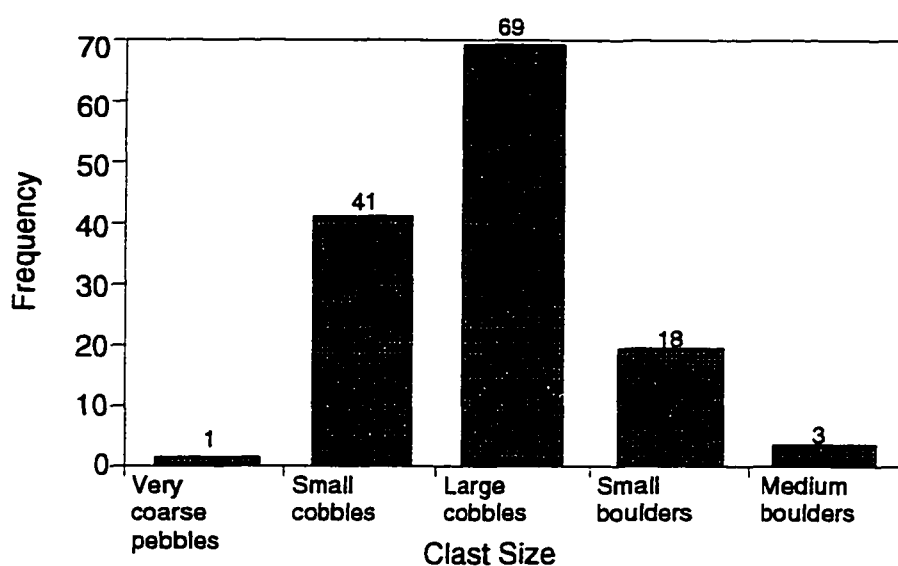


Figure 5.5: Frequency distribution of sliding rocks, by volume. Number of rocks per clast size categories represented on the Racetrack Playa. Grade limits for these groups are as follows: very coarse pebbles (33 to 262 cm³); small cobbles (262 to 2,097 cm³); large cobbles (2,097 to 16,777 cm³); small boulders (16,777 to 134,217 cm³);

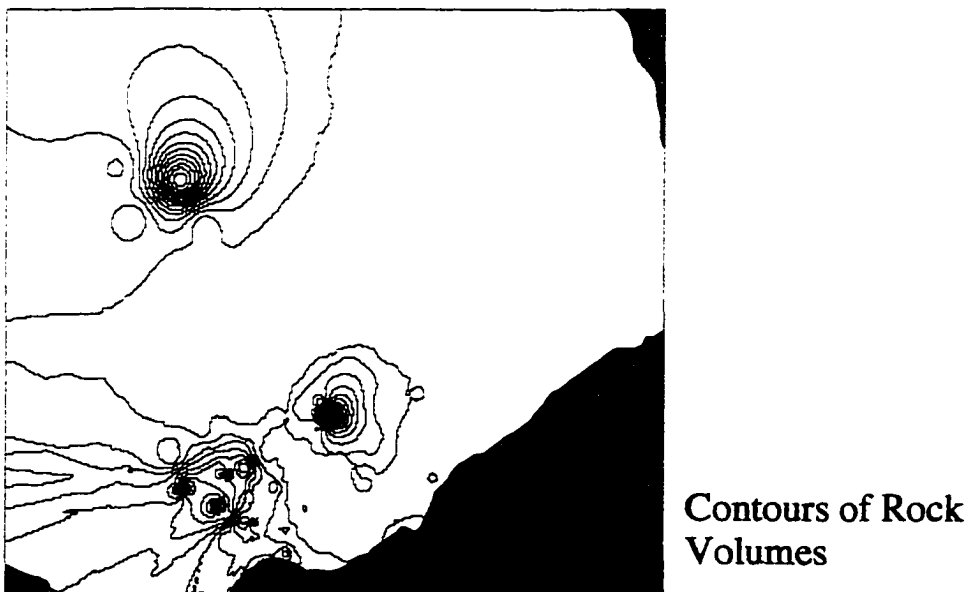
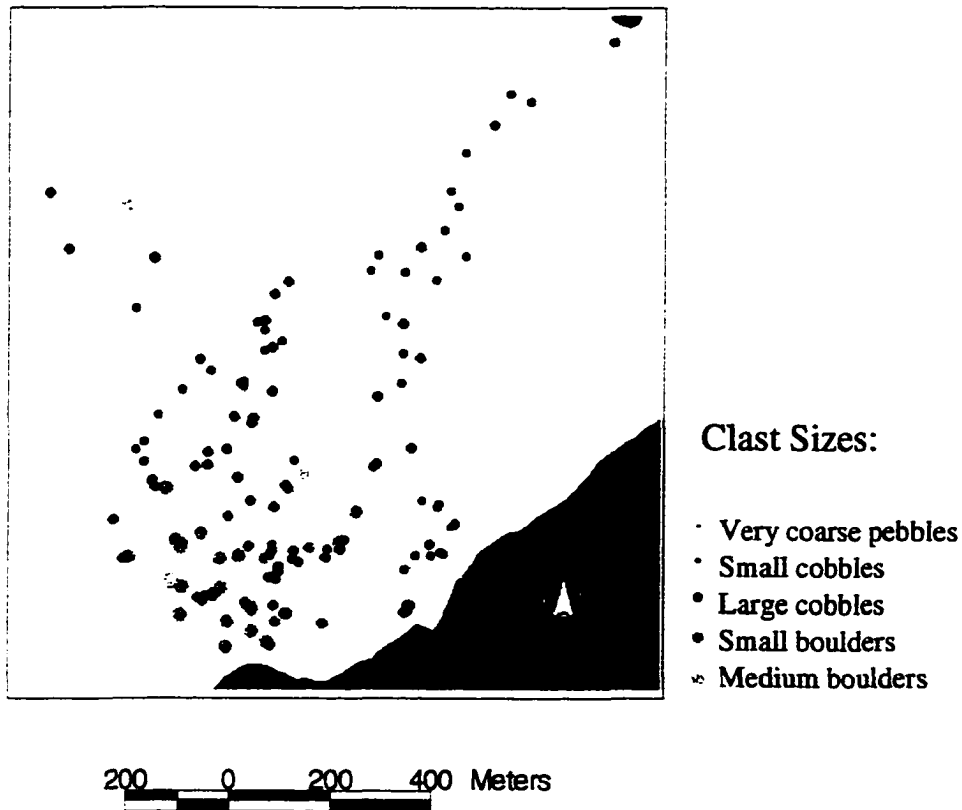


Figure 5.6: Spatial distribution of rocks by volume. Note the variety of rock sizes including the largest boulders in the south-central region of the Racetrack (top). One anomalously voluminous dolomite boulder, #45 (“Karen”) is about 1 kilometer from the southern shoreline, indicating a substantial cumulative journey. Contours (bottom) show the unsorted nature of rocks in the west, and relatively uniform distribution of rocks by size in the east. (Contour interval: 100,000 cubic centimeters.)

5.3.3 Rock Shape Classification

Rock shapes are generally categorized by two geometric qualities: roundness and sphericity. Friedman et al. (1992) define roundness as “the degree of curvature of corners or edges of a particle,” and sphericity as “*equidimensionality* or the degree to which a particle approximates a spheroid (sphere or cube).” Powers (1989) quantifies these descriptors as shown in Figure 5.7. Using this scheme, most Racetrack rocks would be described as spherical-to-subdiscoidal, and angular-to-subangular. Tucker (1996) describes *three* parameters: roundness, sphericity and shape (or form) determined by various ratios of the long, intermediate and short axes. Four resultant classes are presented in Figure 5.8.

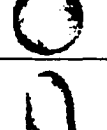
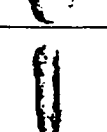
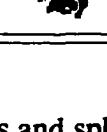
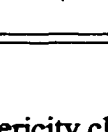
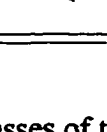
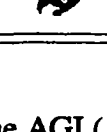
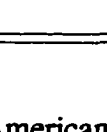
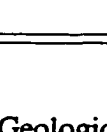
		Roundness					
		Very angular 0.5	Angular 1.5	Sub-angular 2.5	Sub-rounded 3.5	Rounded 4.5	Well-rounded 5.5
Sphericity	Discoidal 0.5						
	Sub-discoidal 1.5						
	Spherical 2.5						
	Sub-prismoidal 3.5						
	Prismoidal 4.5						

Figure 5.7: Roundness and sphericity classes of the AGI (American Geological Institute) *Data Sheets*. (Powers, 1989).

Tucker points out that rocks of uniform composition (such as dolostones) tend to give rise to equant/spherical particles as is the case on the Racetrack.

Since most sliding rocks are both relatively angular and relatively spherical, a quantified classification system was developed to discern the subtle differences among otherwise similarly-described shapes.

Since the total contact area and *footprint* of a rock on the playa surface directly contribute to frictional forces, rocks were classified according to shape using three profile descriptors. Digital images each rock (taken from directly overhead) were used to compile this database after field work was completed (see Appendix I). The number of rock corners (“noses”), indentations (“concavities”) and aspect ratio (length ÷ width) were among the shape descriptors assigned. Figure 5.9 shows a summary of rock shapes and associated values.

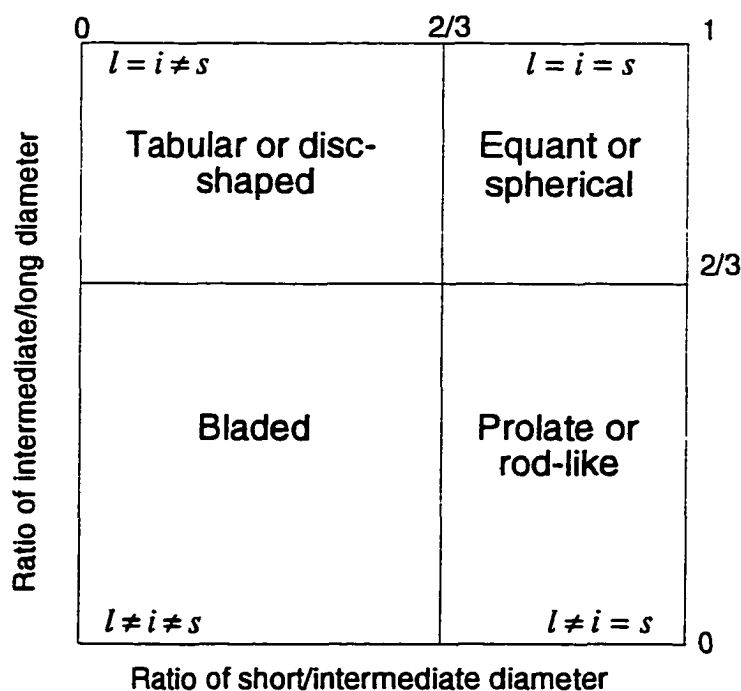


Figure 5.8: Four classes of grain or clast shape. Diagram refers to the long (*l*), intermediate (*i*), and short (*s*) axes of rocks. After Tucker, 1996.

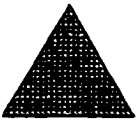
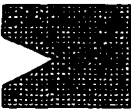
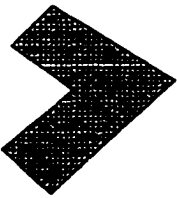
Rock Profile	Noses	Concavities	Aspect Ratio (Length/Width)
	0	0	1
	4	0	1
	2	0	2
	3	0	1
	4	0	4
	6	1	1
	5	1	1
	1	1	1

Figure 5.9: Sample rock shapes as viewed from above are described by three numerical fields. Rocks with less motion-resistant footprints tend to be described by lower numbers using this scheme.

Complete data for all rocks sampled are listed in Table G2 in Appendix G. Histograms of rock shape frequency distributions by descriptor and maps of spatial distributions of shape classes are found in Figures 5.10 (page 140), 5.11 (page 141) and 5.12 (page 142). A “typical” sliding rock as calculated from sample means has 4.03 corners, 0.36 concavities and an aspect ratio of 1.54. Maximum number of “noses” (9) and maximum number of concavities (3) were distinctions both possessed by rock 123 “Amanda,” a flat slab of dolomite with a highly irregular footprint. The least spherical rock, “Catherine,” measured 50 centimeters in length, but only 15 centimeters in width. It is not included in the statistics since its trail was not recorded properly. The highest aspect ratio for a rock in the usable subset is 3.13, for rock 30 (“Theresa”).

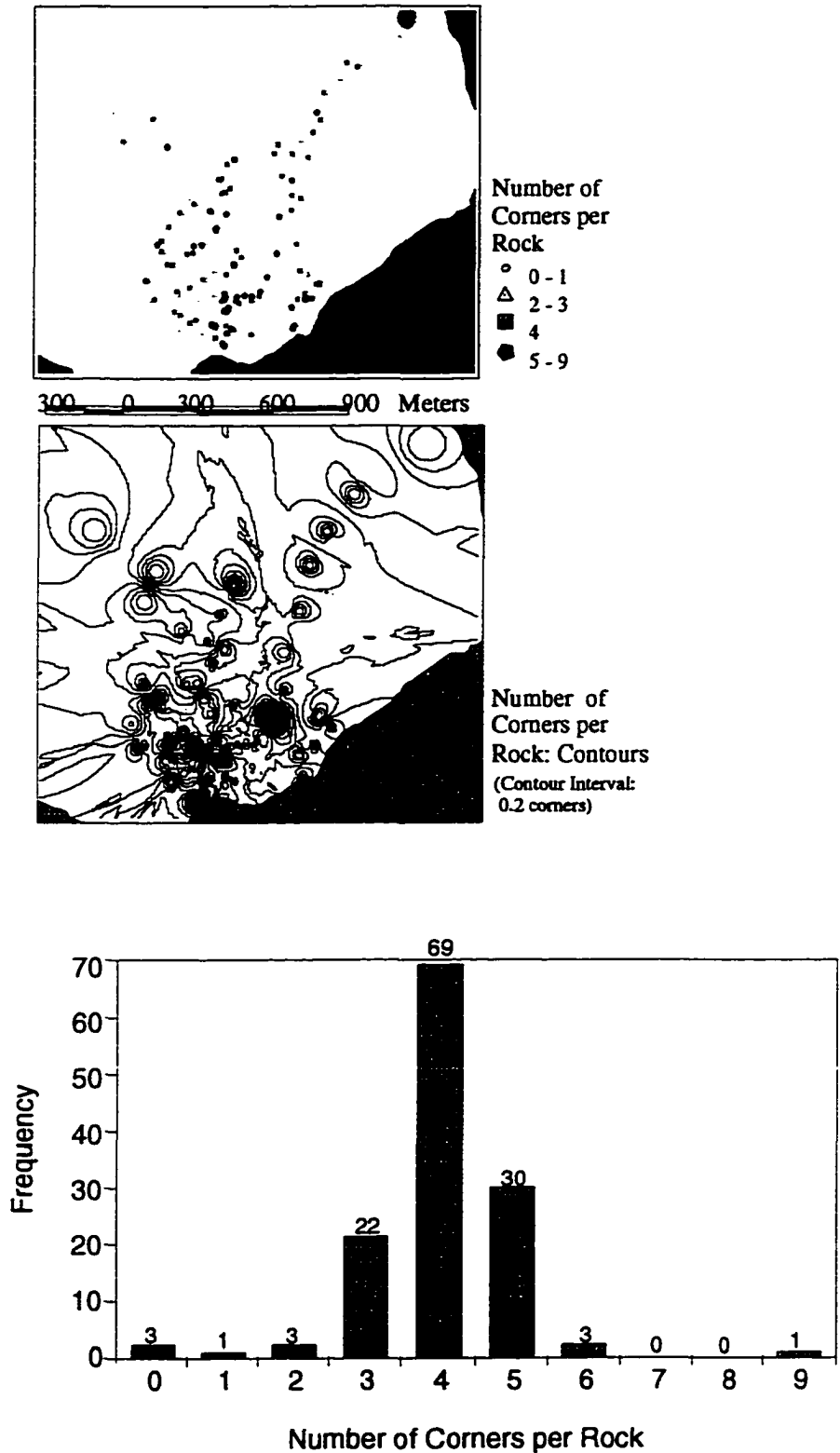


Figure 5.10: Spatial distribution of rocks by number of corners (top); contours of same (middle). Note the general lack of geographic trends to this shape descriptor. The frequency distribution of this variable however is normal (bottom).

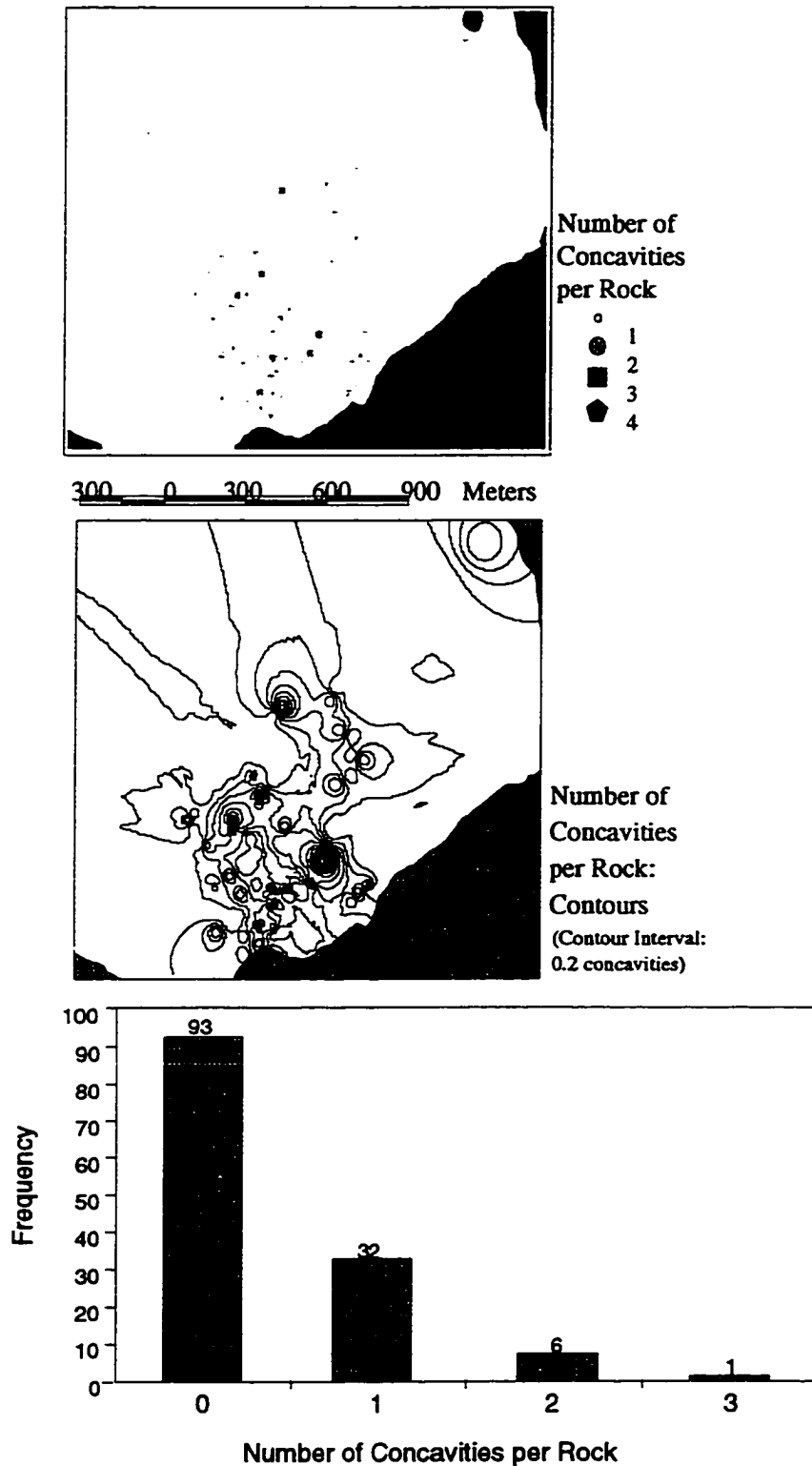


Figure 5.11: Spatial distribution of rocks by number of concavities (top); contours of same (middle). Note the general lack of geographic trends to this shape descriptor. The frequency distribution of this variable (bottom) shows the general convexity of rocks.

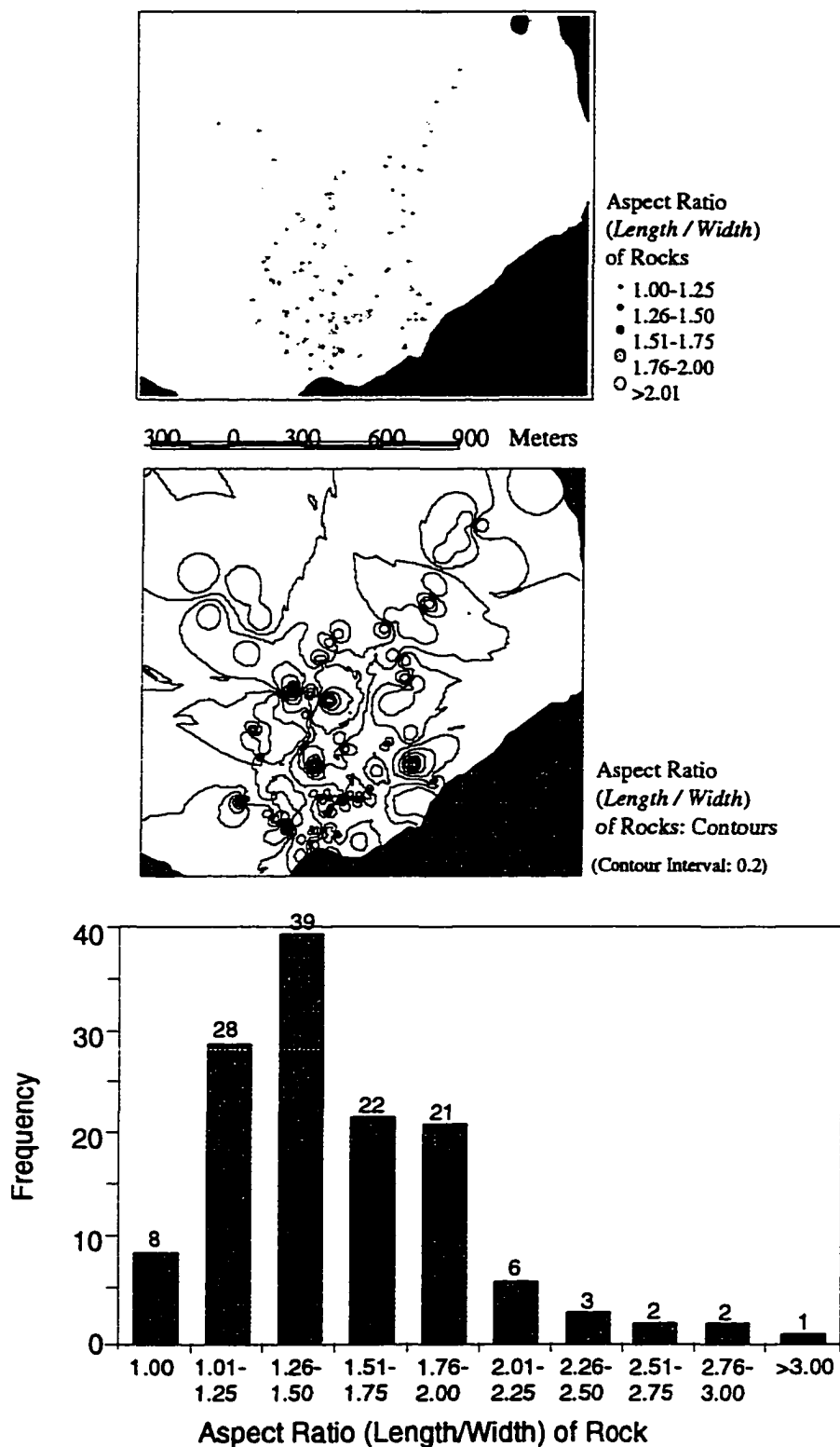


Figure 5.12: Spatial distribution of rocks by aspect ratio (top); contours of same (middle). Note the general lack of geographic trend to this shape descriptor. The frequency distribution of this variable however is relatively normal (bottom).

5.3.4 Trail Length Analyses

The length of trails was measured by ArcView and later imported into Microsoft Excel. *Total trail length* refers to the total distance of motion during a single episode, i.e., the cumulative along-track distance in all directions traveled. A histogram of the frequency of total trail length classes (Figure 5.13) shows that short trails (i.e., under 200 meters in total length) constitute over 50% of the total number mapped in July 1996. The longest trail found was for rock 145 “Diane,” which measured 880.7 meters in total. When considering just the rocks in the 132-rock subset the average trail length is 211.7 meters long. To contrast, when the rocks nearest the road are taken into consideration the mean trail length over the *entire* playa is only 201.9 meters. This calculation reflects disparities in trail characteristics between the western and southern playa sectors. In either

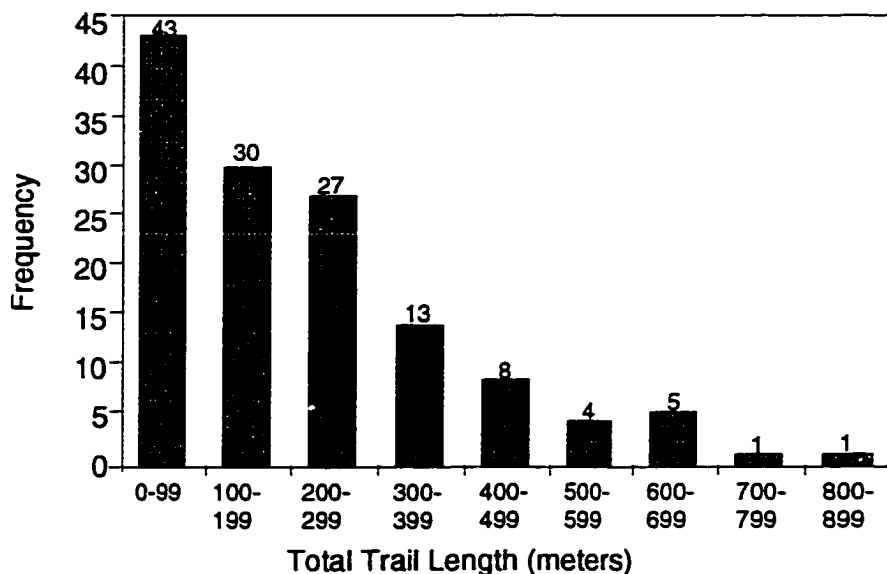


Figure 5.13: Frequency distribution of total trail length classes. Most trails (56%) on the Racetrack in July, 1996 were found to be under 200 meters in total length. Longest trails constituted the smallest groups.

case, rocks without trails (N=7) were not entered into the equations as zeroes. Table G3 in Appendix G shows complete data for trail length.

Cursory examination of the map shown in Figure 5.1 (page 127) reveals that the longest trails were found near the eastern margin of the playa. It seemed likely that a spatial pattern might emerge from plotting trails of similar length. As with other geographic information systems, the ability to sort spatial data by almost any parameter is possible using ArcView. Figures 5.14 through 5.22 show the results of these database queries.

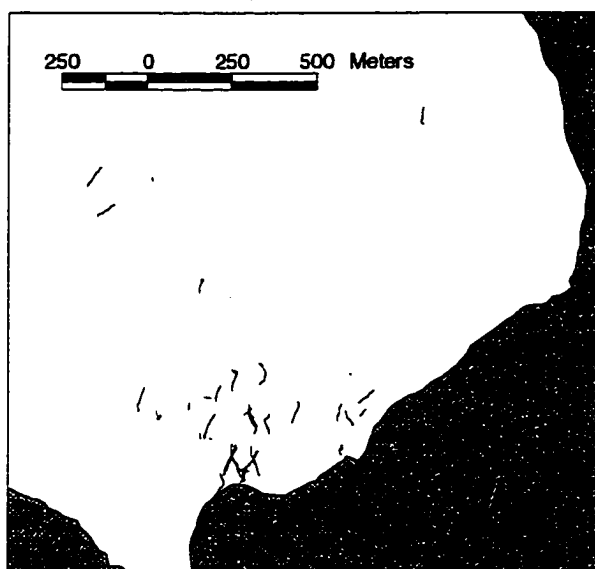


Figure 5.14: Sliding rock trails measuring between 0 and 99 meters in length.

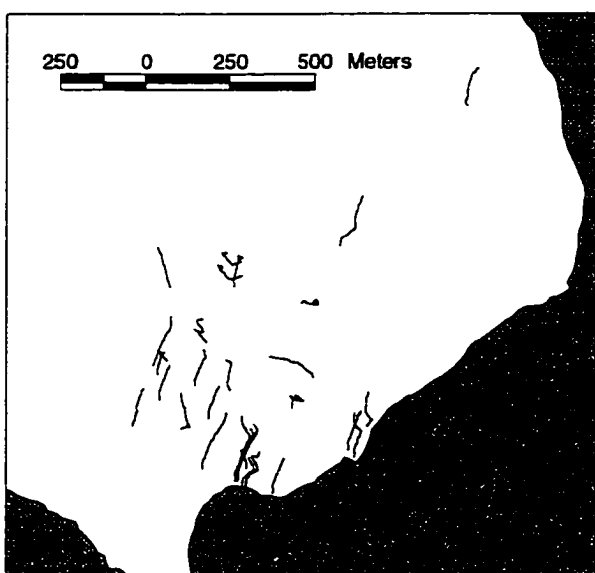


Figure 5.15: Sliding rock trails measuring between 100 and 199 meters in length.

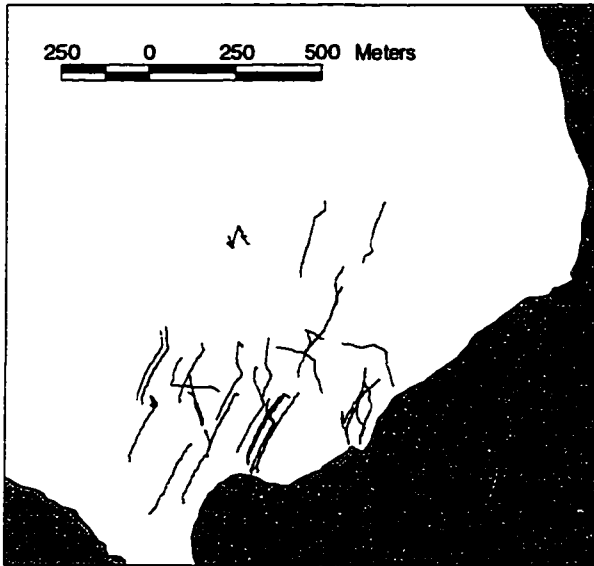


Figure 5.16: Sliding rock trails measuring between 200 and 299 meters in length.

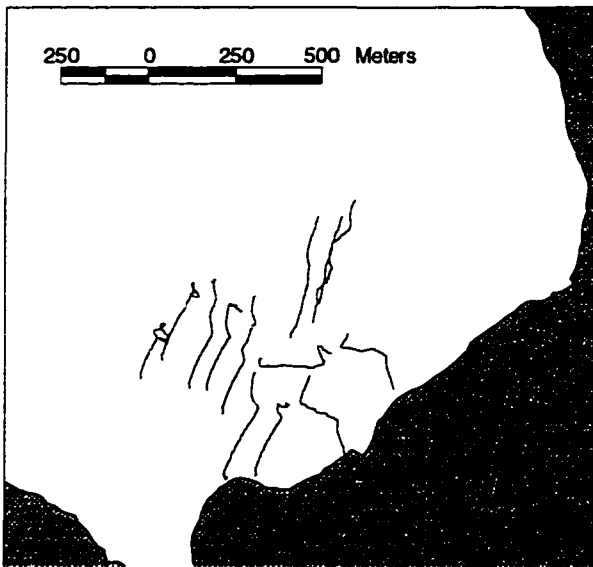


Figure 5.17: Sliding rock trails measuring between 300 and 399 meters in length.

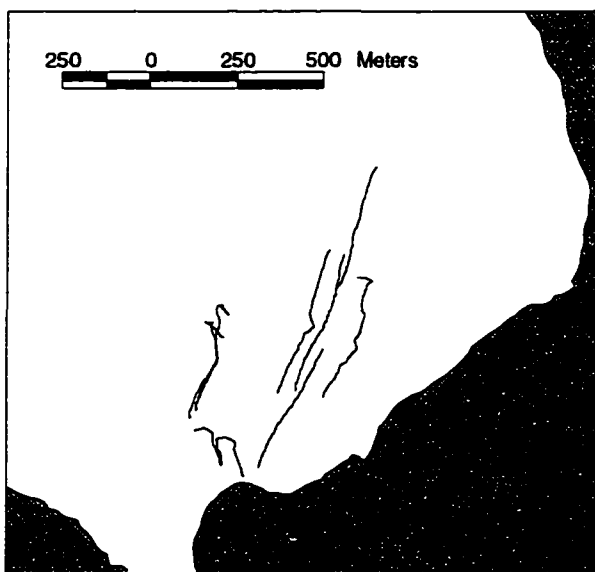


Figure 5.18: Sliding rock trails measuring between 400 and 499 meters in length.

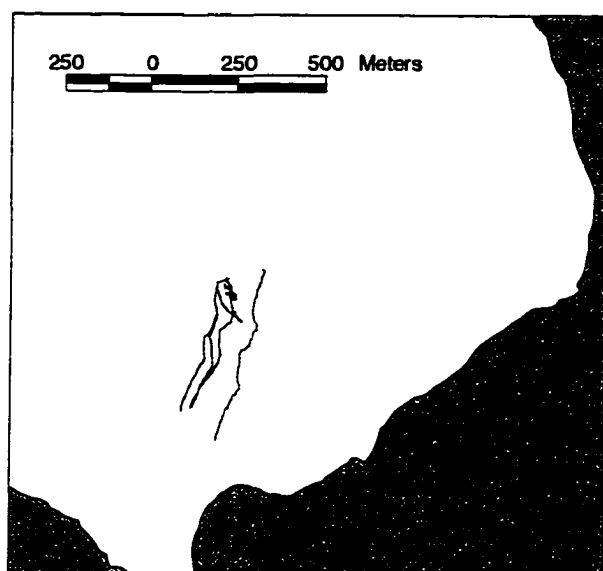


Figure 5.19: Sliding rock trails measuring between 500 and 599 meters in length.

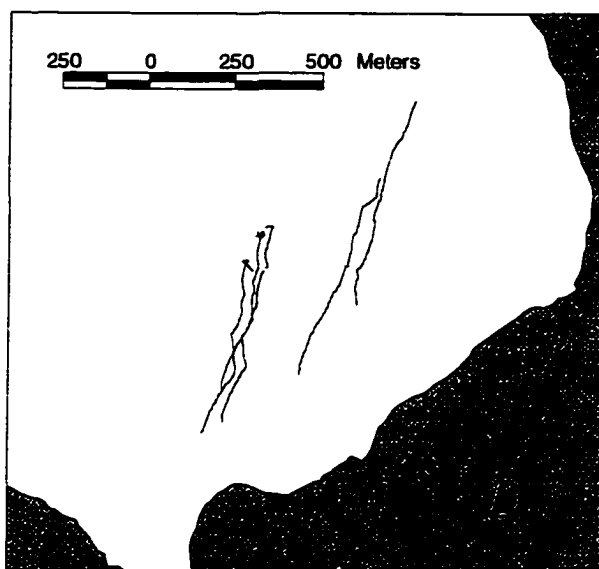


Figure 5.20: Sliding rock trails measuring between 600 and 699 meters in length.

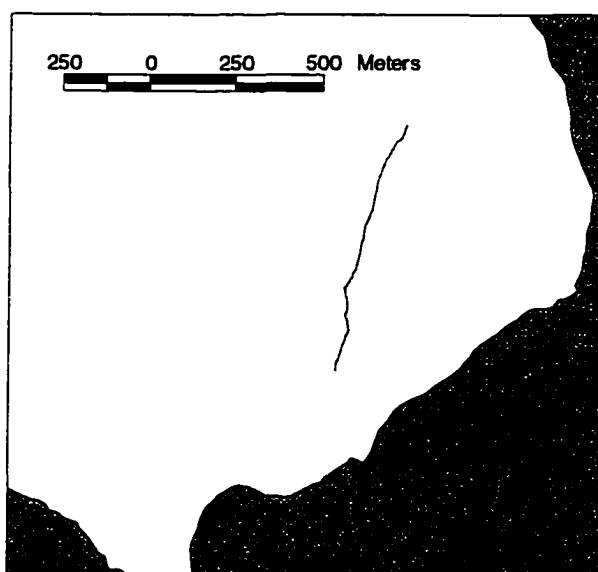


Figure 5.21: Sliding rock trail measuring between 700 and 799 meters in length.

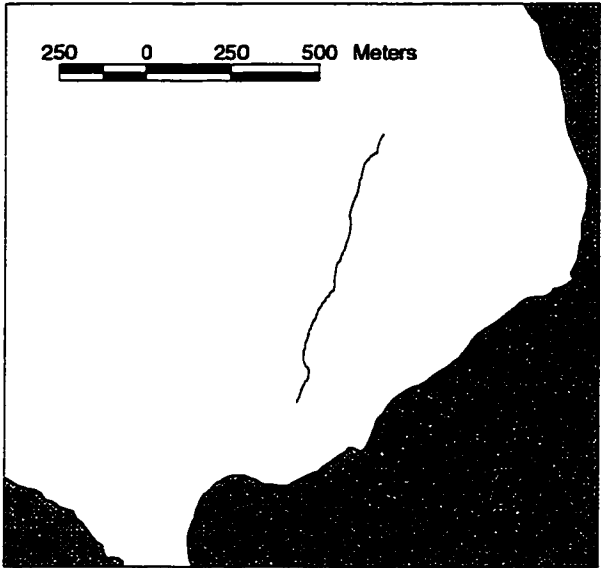


Figure 5.22: Sliding rock trail measuring between 800 and 899 meters in length.

5.3.5 Trail Straightness Analyses

Despite several surveying missions described in Chapter 2, quantified trail straightness data had previously neither been collected nor analyzed. The start point and end point of each trail were captured as the first and last UTM coordinates in each rock’s associated line feature, respectively. Subtracting the end point coordinate from the start point yielded a *direct trail distance*, which is the straight-line measurement from origin to terminus. This derived field appears in Table G3. The UTM coordinates of each trail’s start and end points are listed in the table G4.

One method to quantify the straightness of a trail is to divide the *direct trail distance* by the *total trail distance*. A perfectly straight line would therefore result in a straightness quotient of 1.00, while a highly convoluted trail would yield a significantly smaller quantity. A histogram of this straightness measure shows that the majority of trails are quite straight; most (N = 81) fell within the range of 0.9 to 1.0 (Figure 5.23). Straightness varied from a low of 0.19 (rock 73 “Claudia”) to 0.99 (rock 139 “Agnes”).

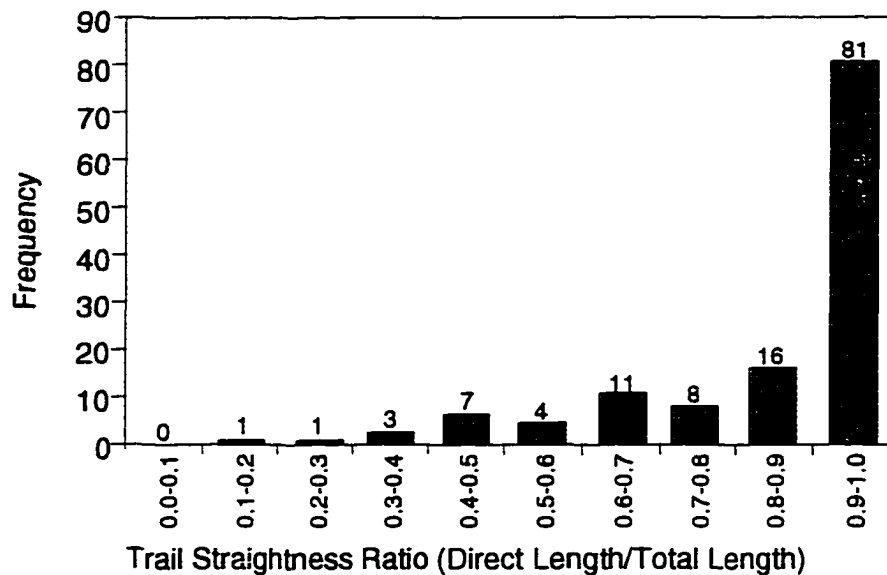


Figure 5.23: Frequency distribution of trails, by straightness. Few trails encountered in July 1996 were erratic. (The straightness measure is the ratio between direct trail length and total trail length; hence a straight line would have a straightness quotient of 1.00.)

Claudia's trail had a total length of 272 meters but it looped back on itself so that its terminus was under 51 meters from its origin. To contrast, the straightest trail measured (139 "Agnes") was only 6 meters long. The average straightness calculated in July 1996 was 0.84 for *all* rocks in the subset; straightness was only slightly lower for granite fragments (0.81). Since granite tends to weather into more rounded shapes than carbonates, it has been suggested (Sharp and Carey, 1976) that trail straightness may be somewhat influenced by lithology. However, this survey shows that the relationship between rock type and trail character is weak, if significant at all.

Examination of the geographic distribution of trail straightness reveals a cluster of circuitous routes traveled by rocks in the central portion of the playa. Figure 5.24 shows trails separated into two categories: greater-than-mean and less-than-mean straightness. Using this grouping, linear trails outnumber meandering trails almost two to one, and they

tend to frame the smaller subset. Figure 5.25 shows a contour map based on the trail straightness field.

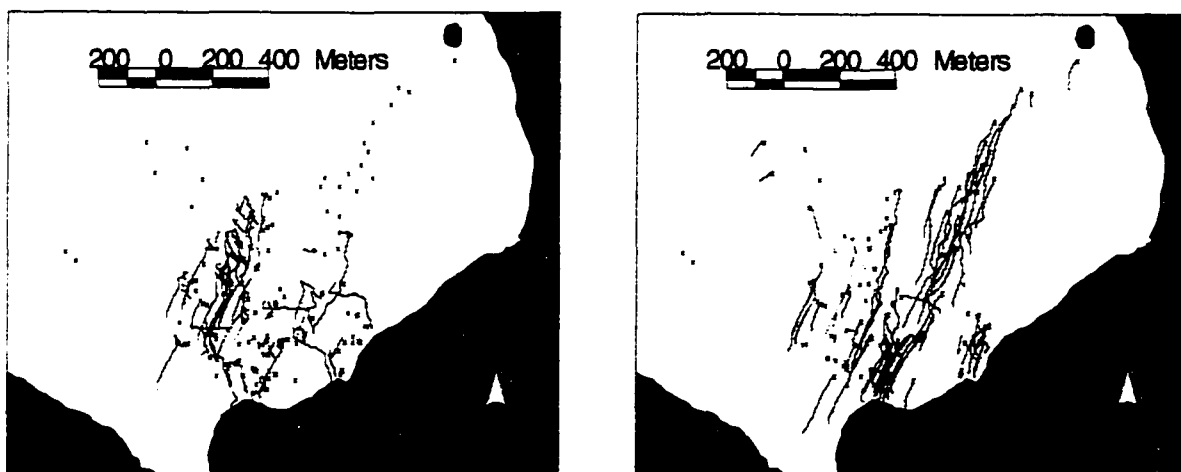


Figure 5.24: Crooked trails (straightness factor < 0.85 , left) versus straight trails (straightness factor > 0.85 , right). A total of 46 trails with lower than average straightness quotients (left) are mostly huddled near the center of the playa. In general, trails with higher-than-average straightness quotients (right) are positioned outside of this central knot. (Rock locations are noted on each map as Xs.)

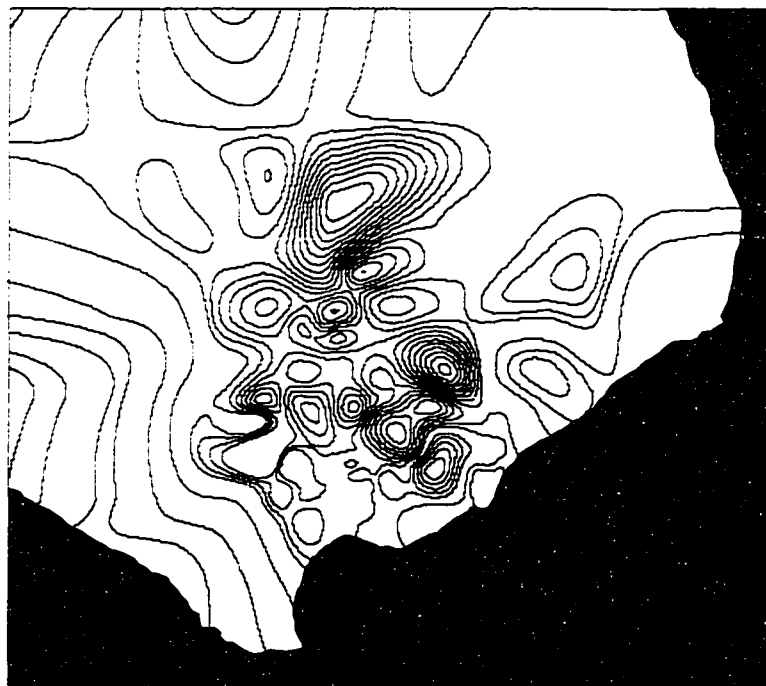


Figure 5.25: Contours of trail straightness quotients. Trail straightness is more uniform on the east and west sides of the boulder field. Pockets of highly irregular trails cause the trail straightness gradient to be greatest in the center of the playa.

5.3.6 Trail Heading Analyses

Every trail was captured as a polyline whose point components were unequally spaced. This was due to variations in walking speed as the trails were initially digitized. When there was a high degree of detail, as was the case with angular routes, corner points and significant curves needed to be included in the traced line. With a sampling frequency of 2 seconds, it was sometimes necessary to slow down while collecting vertices so as to ensure capturing high information content nodes. When mapping relatively straight lines, pacing was more brisk and constant. Variations in distance between vertices are enumerated in Table G4 in Appendix G.

Trails with intricate oscillations may have minimum mapped segment lengths in the millimeter range (e.g., 160 “Helen”) and correspondingly high calculated standard deviations. However, low minimum segment lengths fall within the data’s spatial margin of error and may also be indicative of temporary pauses. Therefore, the correlation between mean mapped segment lengths and trail straightness is weak. The mean minimum segment length for sampled trails was 0.21 meters; mean maximum segment length was 3.3 meters; the mean average segment length was 2.3 meters (indicating that the overall average speed for the field surveyors while marking trails was 1.1 meters per second) with a standard deviation of 0.59 m.

For many analyses trails needed to be made more uniform in segment length. Each trail in the data base was apportioned into 50-centimeter elements using *Simplify*, a C program developed for line generalization (Clarke, Cippolletti and Olsen, 1993). The process inputs the UTM eastings and northings of each point in each trail, and outputs a “simplified” polyline with equidistant vertices. In so doing, values indicating generalized trail

headings were assigned.

Directions of motion for every 50-centimeter segment were assigned corresponding compass “octants” as illustrated by Figure 5.26 for each trail mapped. The line generalization routine also reported the number of turns per trail; the *average* trail was found to consist of 8.0 changes in heading through its route. Tables G5 and G6 in Appendix G contain complete listings of each trail’s constituents.

Figure 5.27 shows resultant means of all trails’ segment headings per octant. Note that for the *average* sliding rock, the greatest constituent heading was in the north-north-east octant (Octant 0). Figure 5.28 shows a rose diagram of the relative percentages of motion by octant.

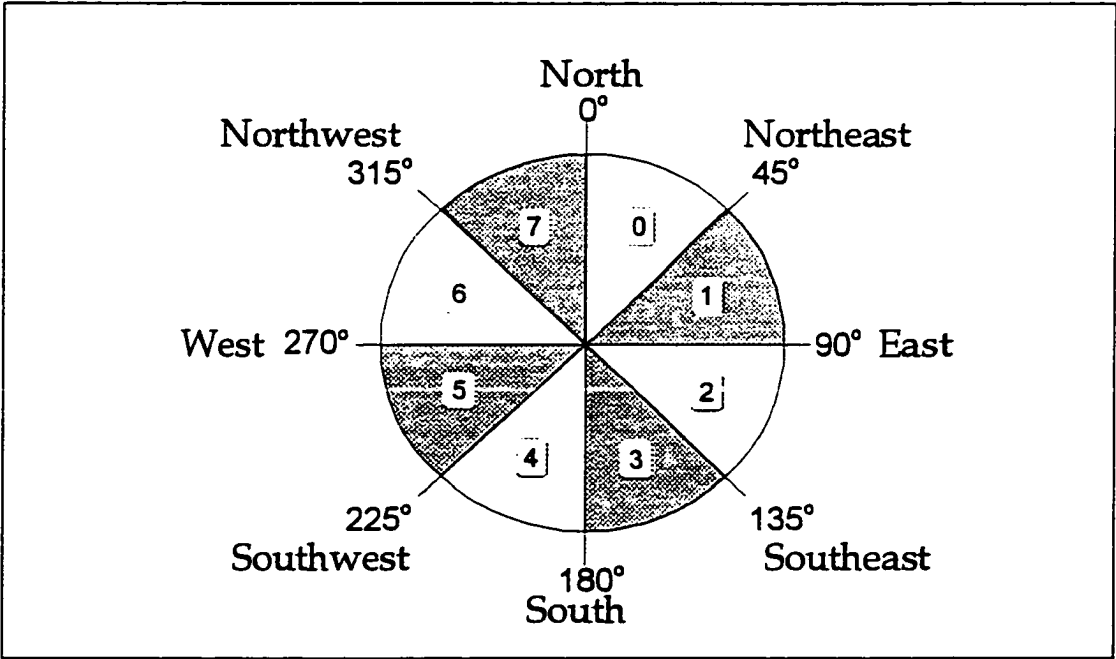


Figure 5.26: Octants of Rock Motion. Trails were divided into 50-centimeter segments. The direction of rock motion in each segment was classified by octant as defined above. Tables G5 and G6 in Appendix G list the details of each rock’s path.

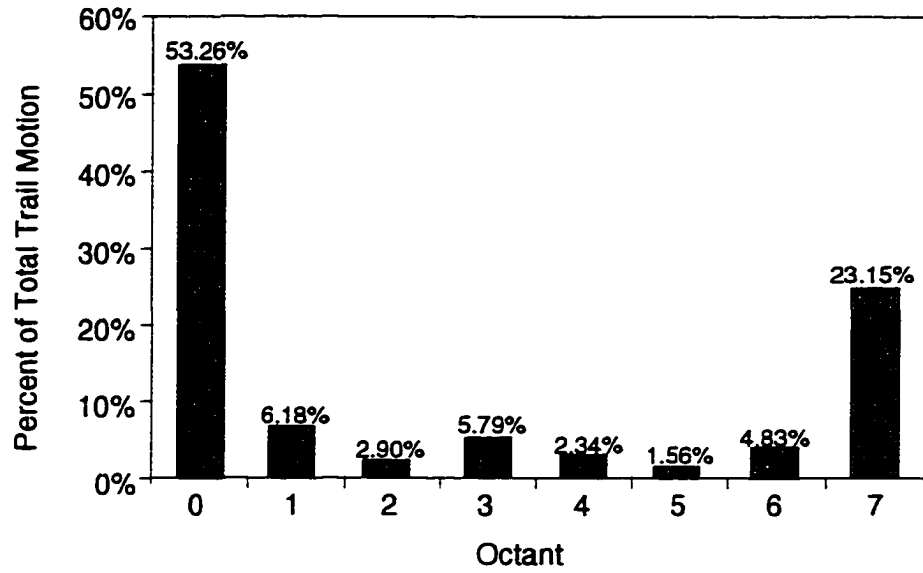


Figure 5.27: Histogram of percentages of motion per octant of the average trail. The greatest component of movement for the *typical* trail lies between due north (0°) and northeast (45°) in octant 0.

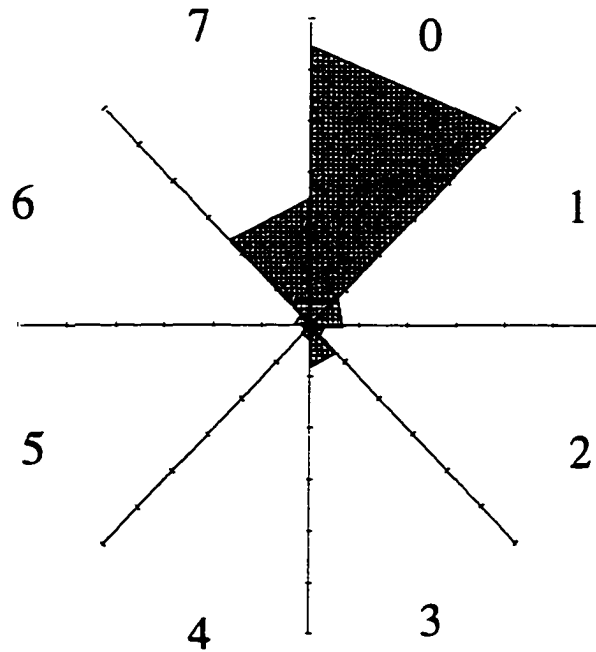


Figure 5.28: Rose diagram of the average trail's heading components. Note that the greatest motion occurs in the north-northeast octant.

5.4 Regression Analyses

As in the past, this survey sought definitive correlations between studied parameters. The measurements and derived data listed in Appendix G presented an almost unlimited number of possible correlations to be tested. Some were performed as a result of hypotheses posed by previous researchers (see “5.4.4 Trail Straightness versus Rock Size” on page 158 and “5.4.5 Trail Straightness versus Rock Shape” on page 159). Many others (see section “5.4.6 Other Relationships” on page 161) were conducted as a result of preliminary principal components analyses on the dozens of fields.

5.4.1 Trail Length Versus Rock Volume

Among the most reasonable assumptions is that larger, heavier rocks would produce shorter trails than smaller, lighter ones. While it was impossible to make such a generalization in the field, analysis of the data afterwards allowed for some rather unexpected results. The scatter plot in Figure 5.29 shows that while there is a *trend* for larger rocks to produce shorter trails, the correlation between the two parameters is not statistically significant. Figure 5.30 shows a similar scatter plot, this time using the trail’s *direct* distance (length of a straight line between trail start and end points). Examination of these regressions shows that trail length is *not* solely a function of rock size.

Despite the surprisingly low correlation coefficients, there is a distinct *tendency* for larger rocks to inscribe shorter trails. The great variation in trail length and large number of outliers within each rock volume category results in seemingly uncorrelated data fields. However, when organizing the data into clast-size groups, a definitive pattern emerges. Figure 5.31 shows the mean trail length for particle size categories.

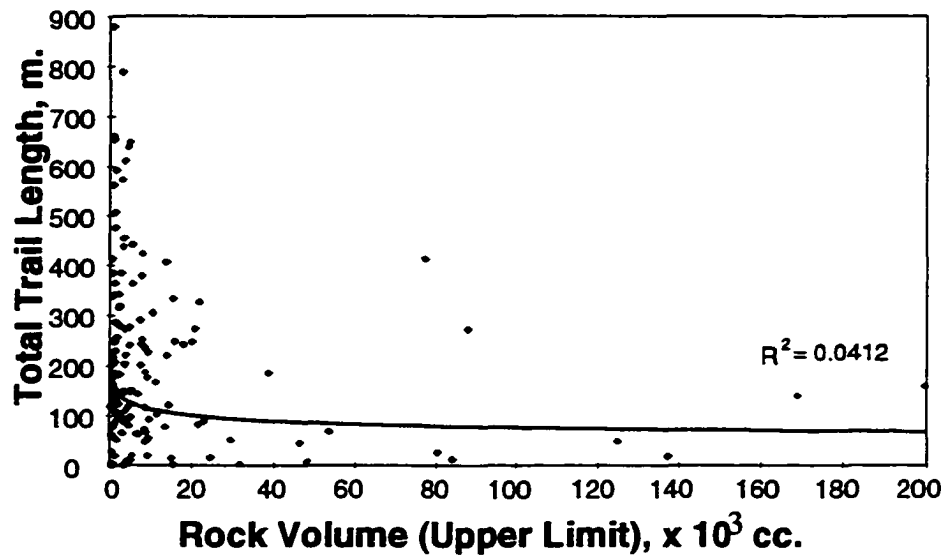


Figure 5.29: Total trail length versus rock volume. Y-axis values are the total distances traveled by each rock, as mapped. The rock volume measurements are *outside estimates* since rock dimensions do not describe perfect cubes or rectangular prisms.

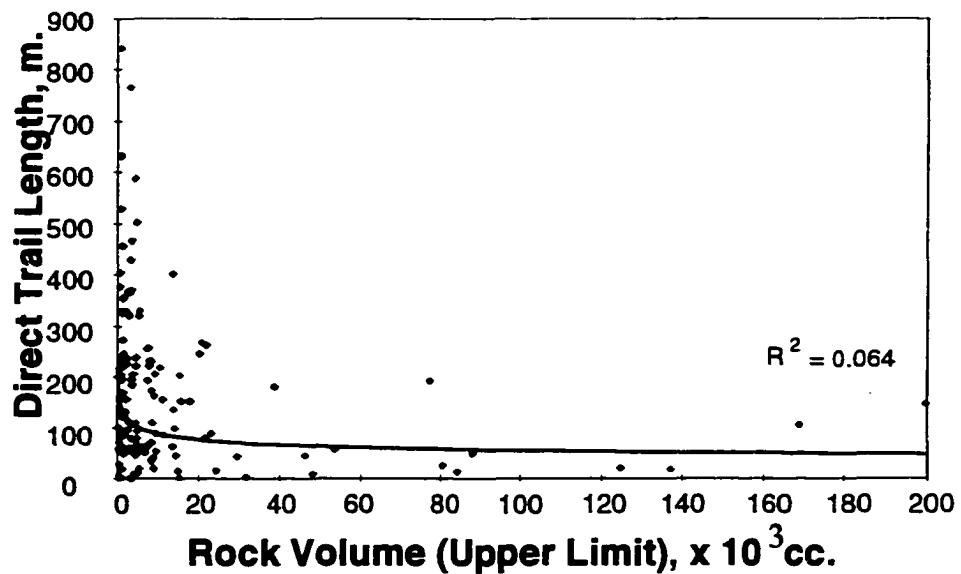


Figure 5.30: Direct trail length versus rock volume. Y-axis values are for straight-line distances between trail start and end points. The rock volume measurements are *outside estimates* since rock dimensions do not describe perfect cubes or rectangular prisms.

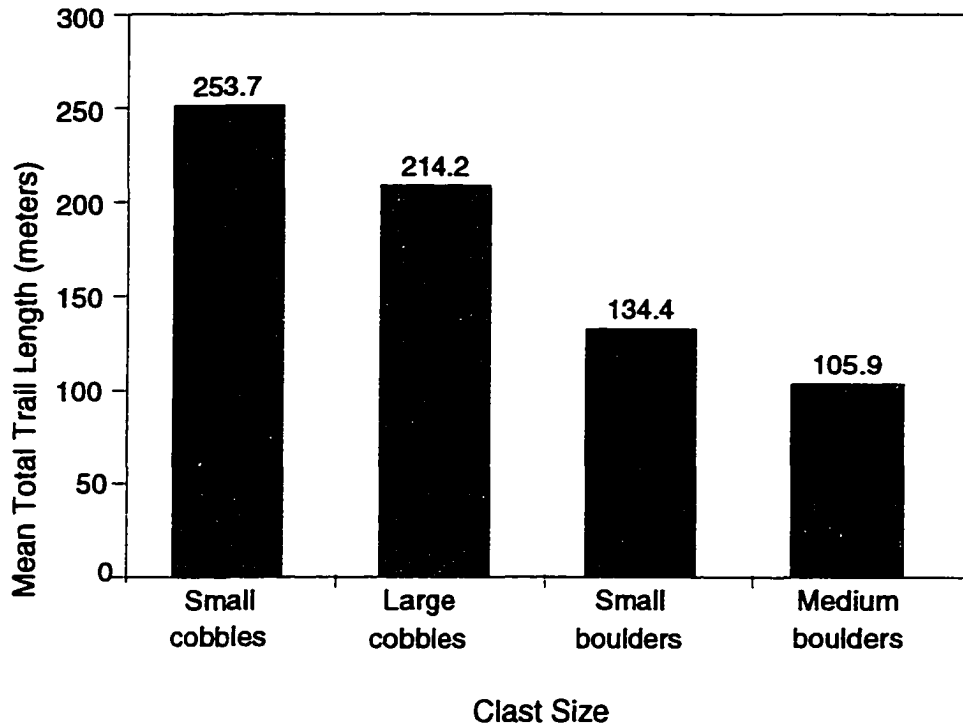


Figure 5.31: Mean trail lengths by clast size. Average trail lengths are greatest for smallest rocks, and lowest for large rocks. The smallest particle size present on the Racetrack (very large pebble) is represented by only one specimen, so it has been omitted from this bar graph.

5.4.2 Trail Length versus Rock Height

The work of Bacon, Cahill and Tombrello (1996) speculated that a rock's extension into the atmospheric boundary layer affects the force exerted on it (see "2.12 Bacon, Cahill and Tombrello, 1996" on page 51). As a result it was important to plot trail length variables against associated rock height dimensions. Figures 5.32 and 5.33 show the results of these two comparisons.

Based on these graphs, it seems unlikely that the height above the playa floor affects the total force on a rock. This may in fact be due to the compression of the atmo-

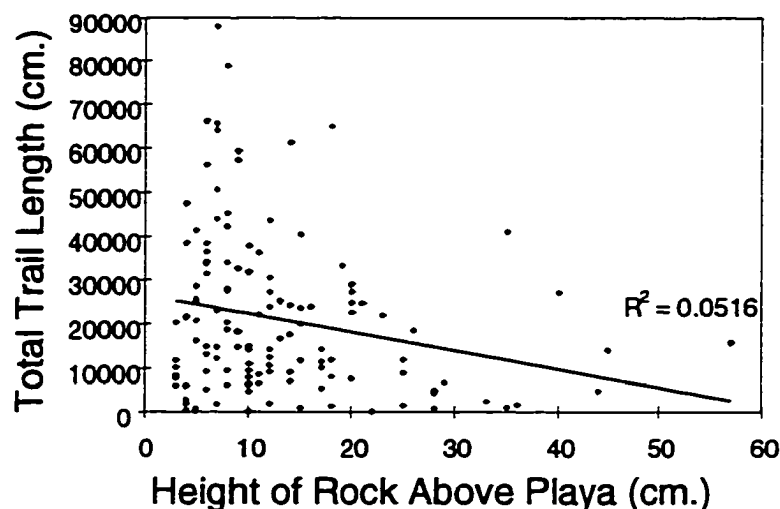


Figure 5.32: Total trail length versus rock height above playa. This regression shows a *inverse* trend between rock length in the Z- dimension and resulting total trail length. The relationship however is extremely weak.

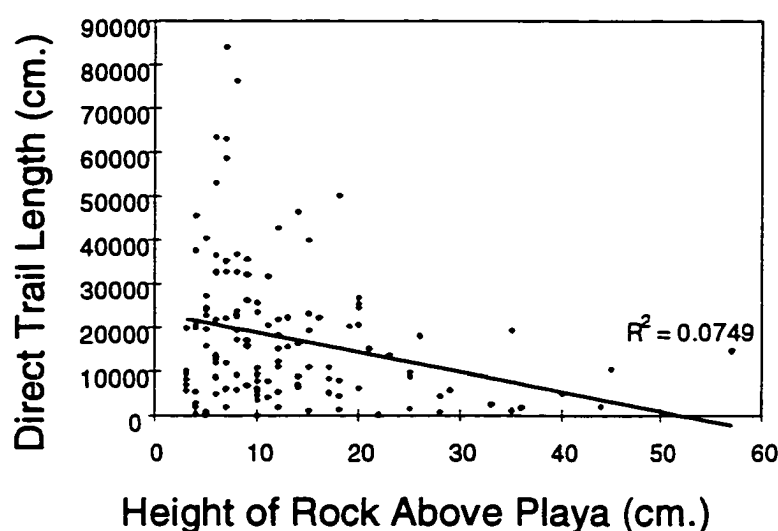


Figure 5.33: Straight-line trail length versus rock height above playa. This regression also shows a *inverse* trend between rock length in the Z- dimension and resulting total trail length. The relationship however is extremely weak.

spheric boundary layer to an extremely thin veneer. Where the boundary layer is very thin, allowing full unimpeded flow only a few centimeters above the playa floor, then one could expect all rocks to be affected equally in this vertical column of air. Only the aerodynamic X-Y shape would change the way rocks responded to the force of rushing air.

Of the 132 rocks sampled, the range in height was from 3 centimeters (six rocks share this measurement) to 57 centimeters (rock 94 “Kitty”). The six shortest rocks have a mean total trail length of 108 meters, while the rock 94 (Kitty) inscribed a path 158 meters long. There is no significant correlation between a rock’s vertical dimension and the ability of that rock to slide.

5.4.3 Trail Length versus Playa-Rock Contact Area

If the degree of extension into the atmospheric boundary layer does not appreciably affect a rock’s movements, then a rock’s contact area on the playa may be more influential. Since a greater cross-sectional (X-Y) area in contact with surface deposits increases the frictional force resisting rock motion, the rocks’ “footprints” were also calculated. A plot of total trail length versus this derived parameter shows a general inverse relationship, but surprisingly, no significant correlation (Figure 5.34).

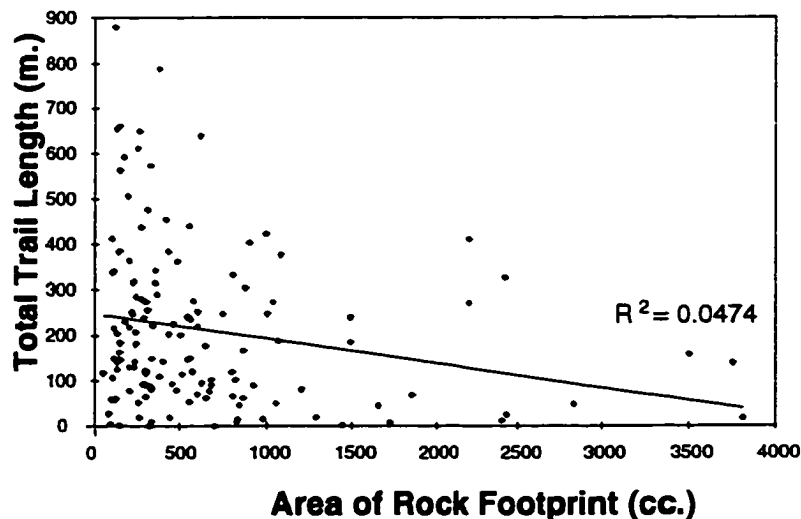


Figure 5.34: Total trail length versus rock footprint area. As total contact area with the playa surface increases, total trail length decreases (due to increased frictional force). The correlation coefficient is surprisingly low.

5.4.4 Trail Straightness versus Rock Size

When the straightness quotient (direct length ÷ total length) of trails is compared to approximate volumes of corresponding rocks, the data appear almost totally uncorrelated. Yet both trail straightness and rock size spatial distributions are not uniform on the playa. Figures 5.24 and 5.25 (page 149) show that trails closest to the eastern boundary of the boulder field are more uniformly straight. Figure 5.6 (page 135) shows that the rocks that produced these relatively-direct trails are of predominantly one clast size. Seventy-four percent of the eastern-margin rocks are small cobbles while 26% are large cobbles. This contrasts dramatically with the general distribution of rocks on the playa: Only 31% are small cobbles, and 52% are large cobbles (see Figure 5.5, page 134). No other particle sizes are represented in this geographically-defined subgroup. Figure 5.35 shows a map of this natural cluster.

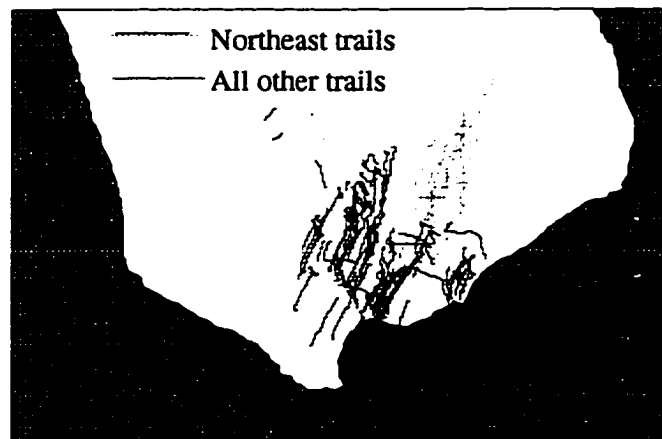


Figure 5.35: A natural division occurs between northeast rocks/trails, and all others. Whereas five clast size categories are represented on the Racetrack, only two of them (small cobbles, large cobbles) are present in the northeast. The average straightness of *all* trails on the playa is 0.85, but the average straightness for northeast trails is 0.92. Average straightness for just small cobbles in the northeast is 0.96. The subset of only northeast trails is quantifiably different from those distributed elsewhere on the Racetrack. The northeast subset consists of rocks 141 - 160.

When excluding this anomalously undifferentiated subset from the majority of trails on the Racetrack, there appears to be a general trend for larger rocks to produce straighter trails. Figure 5.36 shows a frequency distribution of mean straightness quotients per clast size categories for largest rocks on the playa's interior and southern sectors.

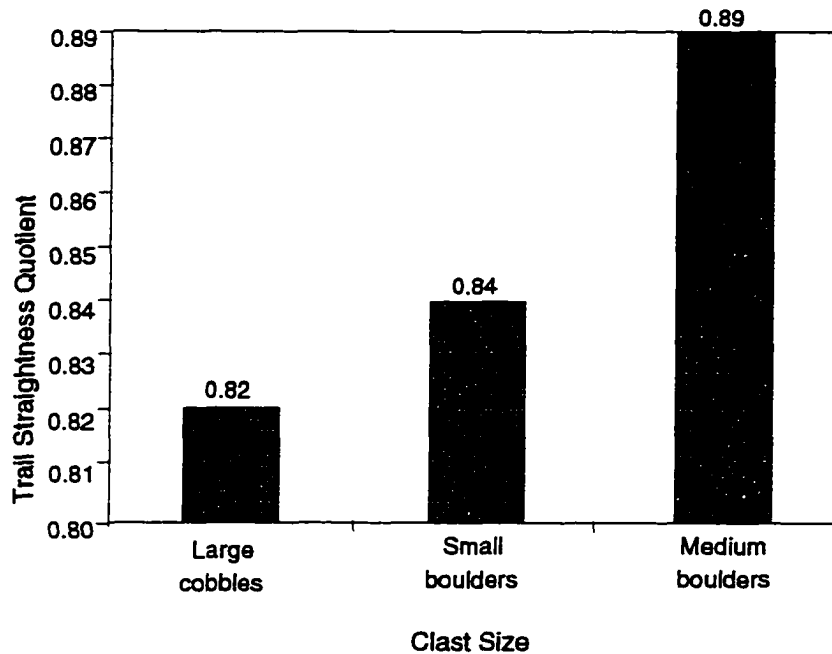


Figure 5.36: Mean trail straightness quotients per particle size, excluding northeastern rocks (141-160). There is a general trend for larger rocks to produce straighter trails.

5.4.5 Trail Straightness versus Rock Shape

Figure 5.1 (page 127) shows great variability in the nature of sliding rock trails. During the mapping phase it was evident that some rocks produced highly regular, straight trails while others formed thoroughly convoluted paths. Sharp and Carey (1976) concluded that the more rounded rocks produced the most erratic trails. The footprint of each rock on the playa surface was assumed to be an important factor in how the rock moved; shape descriptors (discussed in “5.3.3 Rock Shape Classification” on page 136) were used

as quantified measures of rock morphology. To test how the nature of rock shape influenced ultimate trail character, scatter plots focusing on the southern trails and rock shape descriptors were constructed using Microsoft Excel.

Data gleaned from G2 and G3 (Appendix G) were combined in a variety of ways to result in several regression analyses (Figures 5.37, 5.38 and 5.39). Based on these data, it may be concluded that a rock's footprint does not appreciably affect trail straightness.

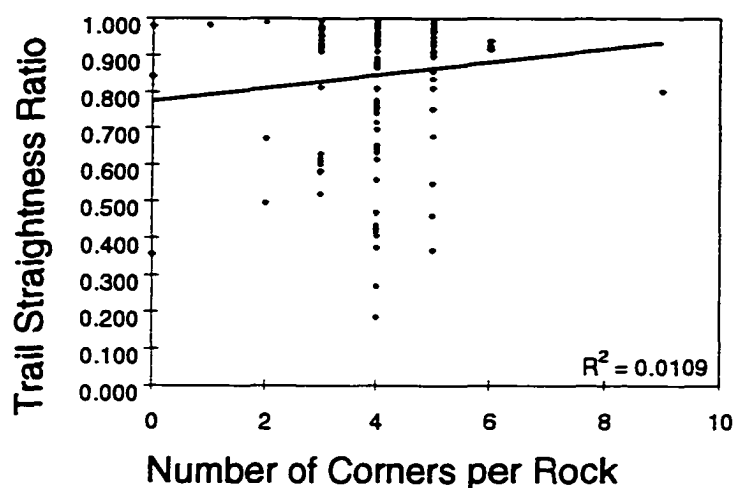


Figure 5.37: Number of corners (“noses”) per rock versus trail straightness. The low correlation coefficient suggests that the angularity of the rock’s footprint has little to do with the directness of its motion.

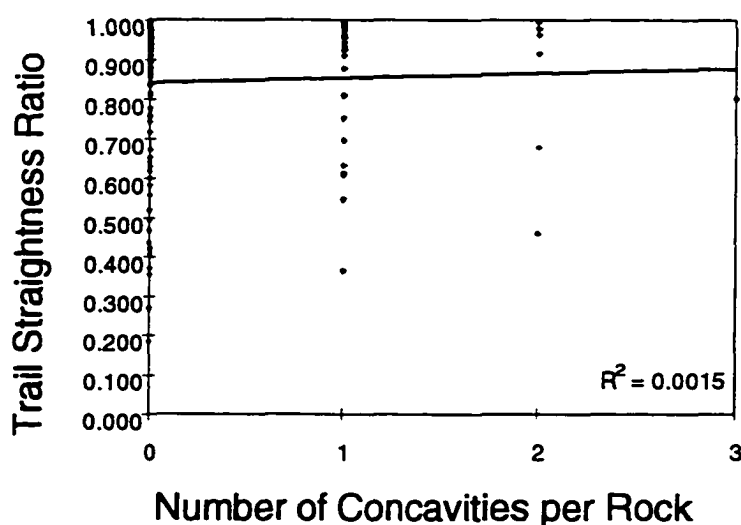


Figure 5.38: Number of concavities per rock versus trail straightness. The low correlation coefficient suggests that the number of indentations in the rock’s footprint has little to do with the rock’s motion.

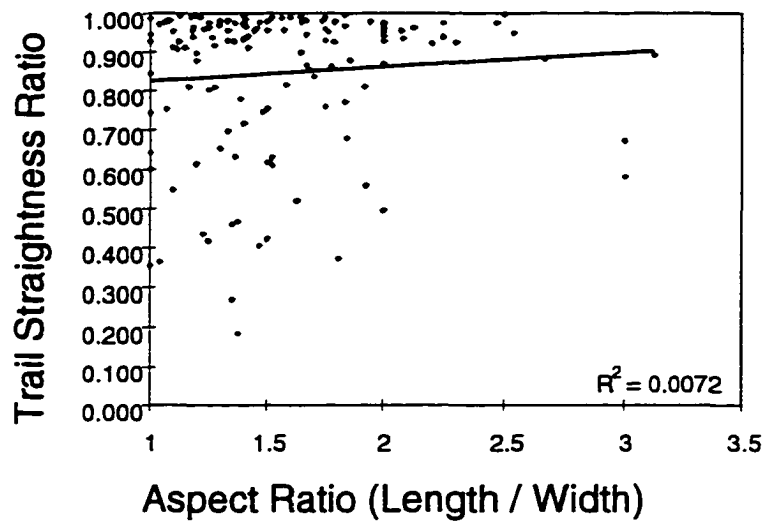


Figure 5.39: Aspect ratio of rocks versus associated trail straightness. Roundest and squarest rocks have aspect ratios approaching 1.0, and at best a very weak trend to produce more erratic trails.

5.4.6 Other Relationships

The relationships that had been *expected* to show strong trends (i.e., trail length versus rock volume, page 153; trail length versus rock height, page 155; trail straightness versus rock shape, page 159) showed no correlation. Therefore it was essential to examine the data for unexpected relationships. The tables in Appendix G contain just over 50 data categories, necessitating $49! (6 \times 10^{62})$ scatter plots to illustrate all relationships possible. Exporting the tables from Microsoft Excel, it was possible to import the data to a statistical package for further inspection. SAS Institute's *Jump* software package was used to conduct principal component analyses on the entire table.

Principal components analysis is a process employed to de-emphasize low-information content data, removing or reducing data redundancy. The procedure compresses information contained in an original n -field data set into *fewer-than- n* “components.”

These decorrelated components are amalgams of the original fields that emphasize high-information data. When such an analysis was run on the data, the results were scrutinized for high loadings in the first principal component, then in the second principal component, and so on. These loadings signified possible correlations between fields, and provided the impetus to run regression analyses on several related parameters.

Extra fields were added to the data; of significant interest was the derived X (east-west), Y (north-south) and straight line distance to the springs (previously described in “4.2.3 Hydrologic Features” on page 87) of trail start points and end points. While the general trends toward longer trails, straighter trails and smaller rocks were evident while progressing eastward during the mapping project, it was important to check for any statistically significant correlations between trail character and proximity to the hydrologic features. Table G7 in Appendix G shows the results of the distance measurements.

All of the scatter plots were constructed using Microsoft Excel; the nongraphical results of these regressions (in the form of r^2 values) are listed in Table 5.1. Data are listed in order of decreasing correlation coefficients.

Some of the relationships are remarkable in their virtual *lack* of correlation.

Table 5.1: Representative Regression Analyses

X variable	Y variable	Relationship (+ = direct; - = inverse)	Correlation Coefficient (r^2)
Total Trail Length (meters)	Number of <i>simplified</i> trail turns	+	0.5948
Direct Trail Length (meters)	Number of <i>simplified</i> trail turns	+	0.4073
Straight-line Distance to Springs of trail end- point (meters)	Direct Trail Length (meters)	-	0.3442

Table 5.1: Representative Regression Analyses

X variable	Y variable	Relationship (+ = direct; - = inverse)	Correlation Coefficient (r^2)
Straight-line Distance to Springs of trail end-point (meters)	Total Trail Length (meters)	-	0.2975
Direct Trail Length (meters)	Percent of Motion in Octant 0 (N-NE)	+	0.1935
Rock Volume (cubic centimeters)	Octant 6 Trail Component (W-NW)	+	0.1892
Direct Length of trails under 400 meters	Octant 3 Trail Component (S-SE)	-	0.1733
Representative Rock Length (cm.)	Octant 6 (W-NW) Trail Component	+	0.1522
Direct Length of Trails over 300 meters	Octant 0 (N-NE) Trail Component	+	0.1357
Straight-Line Distance to Springs of Trails >1000 m. to Start Point	Octant 0 (N-NE) Trail Component	+	0.1190
East-West (X) Distance to Springs of Trail end-point (meters)	Total Trail Length (meters)	-	0.1170
Straight-line Distance to Springs of trail end-point (meters)	Rock Length (cm.)	+	0.1030
North-South (Y) Distance to Springs of Trail Start Point (meters)	Representative Rock Length (cm.)	+	0.0996
Straight-line Distance to Springs of trail end-point (meters)	Representative Rock Length (cm.)	+	0.0926
Height of Rock Above Playa (cm.)	Direct Trail Length (meters)	-	0.0764
Representative Rock Length (cm.)	Direct Trail Length (meters)	-	0.0633

Table 5.1: Representative Regression Analyses

X variable	Y variable	Relationship (+ = direct; - = inverse)	Correlation Coefficient (r^2)
East-West (X) Distance to Springs of Trail Start-point (meters)	Direct Trail Length (meters)	-	0.0533
East-West (X) Distance to Springs of Trail Start-point (meters)	Total Trail Length (meters)	-	0.0432
Height of Rock Above Playa (cm.)	Total Trail Length (meters)	-	0.0417
UTM Easting of Trail Start Point	Total Trail Length (meters)	+	0.0390
Rock Volume (cubic centimeters)	Total Trail Length (meters)	-	0.0310
Straight-Line Distance to Springs of Trail Start Point	Octant 0 (N-NE) Trail Component	+	0.0227
Height of Rock Above Playa (cm.)	Straightness Ratio of Trails	-	0.0225
North-South (Y) Distance to Springs of Trail Start-point (meters)	Straightness Ratio of Trails	-	0.0201
Total Trail Length (meters)	Straightness Ratio of Trail	-	0.0196
Octant 3 (S-SE) Trail Component	Representative Rock Length (cm.)	+	0.0196
Straight-line Distance to Springs of trail Start-point (meters)	Direct Trail Length (meters)	-	0.0177
UTM Northing of Trail Start Point	Total Trail Length (meters)	-	0.0172
North-South (Y) Distance to Springs of Trail Start-point (meters)	Representative Rock Length (cm.)	+	0.0168

Table 5.1: Representative Regression Analyses

X variable	Y variable	Relationship (+ = direct; - = inverse)	Correlation Coefficient (r^2)
Σ Shape Descriptors: Corners + Concavities + Aspect Ratio	Straight-line Distance to Springs of Trail Start- point (meters)	-	0.0157
Straight-line Distance to Springs of Trail Start- point (meters)	Total Trail Length (meters)	-	0.0146
UTM Easting of Trail End-point	Trail Straightness Ratio	+	0.0139
Straight-line Distance to Springs of trail Start- point (meters)	Octant 2 (E-SE) Trail Component	-	0.0130
Rock Volume (cubic centimeters)	Number of Turns per Trail	-	0.0119
Total Trail Length (meters)	Octant 5 (W-SW) Trail Component	+	0.0105
UTM Easting of Trail Start Point	Trail Straightness Ratio	+	0.0091
Total Trail Length (meters)	Octant 3 (S-SE) Trail Component	-	0.0084
Representative Rock Length (cm.)	Number of Turns per Trail	-	0.0078
Representative Rock Length (cm.)	Octant 5 (S-SW) Trail Component	+	0.0056
Straight-Line Distance to Springs of Trail End Point	Straightness Ratio of Trail	-	0.0055
UTM Northing of Trail End Point	Straightness Ratio of Trail	+	0.0041
North-South (Y) Dis- tance of Springs to Trail Start Point	Straightness Ratio of Trail	-	0.0028

Table 5.1: Representative Regression Analyses

X variable	Y variable	Relationship (+ = direct; - = inverse)	Correlation Coefficient (r^2)
Straight-Line Distance to Springs of Trail Start Point	Total Number of Turns per Trail	-	0.0023
Octant 2 (E-SE) Trail Component	Number of "Noses" per Rock	+	0.0022
Total Trail Length (meters)	Octant 6 (W-NW) Trail Motion	-	0.0016
Straight-Line Distance to Springs of Trail Start Point	Octant 2 (E-SE) Trail Component	- (weak)	0.0013
Octant 2 (E-SE) Trail Component	Σ Shape Descriptors: Corners + Concavities + Aspect Ratio	+ (weak)	0.0011
UTM Northing of Trail End Point	Straightness Ratio of Trail	-	0.0011
Straight-Line Distance to Springs of Trail Start Point	Straightness Ratio of Trail	+ (weak)	0.0003
North-South (Y) Distance to Springs of Trail Start Point	Straightness Ratio of Trail	+	0.0001

The data collected showed a greater degree of chaotic tendency than expected.

When trail character is compared to rock morphology, only very weak trends emerge. The strongest correlations, as indicated by this chart, involved spatially-controlled factors. Trail lengths and straightness quotients seem most dependent on geographic location on the playa, and least dependent on the nature of the rocks inscribing them. Geomorphological analysis of the surrounding landforms provided some positive correlations implicating the significance of terrain configurations on the sliding rock phenomenon. A complete discussion follows in Chapter 6.

Chapter 6

Terrain Analysis

Given the emerging spatial patterns of the southern sliding rock field, further analyses were conducted in an attempt to link the Racetrack's unusual surface phenomena to the surrounding terrain. By placing the playa within the context of its neighboring topography, the causative effects of wind channeling were hypothesized.

6.1 DEM Data Transformations

A three-by-three cluster of Digital Elevation Models (DEMs) of the Racetrack Playa and vicinity were purchased from the USGS. All DEMs are categorized as "Level 1" data sets (see "3.12 DEM Data Accuracy" on page 76), indicating that they are of the highest accuracy possible under current data production methods.

While it was initially assumed that all nine DEMs would be spliced together into one data set this ultimately proved superfluous. The entire boundary of the Racetrack Playa is luckily situated near the middle of the Ubehebe Peak 7.5-minute quadrangle, so seaming this data set to any of the other contiguous eight was not necessary. The lakebed is surrounded by mountains included in the Ubehebe Peak quad. Since the sliding rock phenomenon is spatially localized, adding more detail to the periphery served only to add unnecessarily to the volume of the data set. The terrain analyses that followed were com-

putationally intensive, even for a single file. Practicality dictated limiting analysis to the central DEM.

The data sets were delivered via CD-ROM. Each file, in its raw ASCII format, embodied about 1 Megabyte of data. Before the DEMs could be read by ArcView or Arc/Info, they had to have line delimiters added to result in a flat file of columns and rows. This was achieved using the UNIX *dd* command. The result was a file of 30-meter-square pixels, each assigned an elevation in meters.

The files were imported to ArcView by converting the delimited files to Arc/Info “grid” format. As grids, ArcView was capable of reading each raster file when the Spatial Analyst extension was made active: this extension is an add-on program that allows for manipulation of elevation data. Figure 3.6 (page 79) shows some of the derived products composed using the Spatial Analyst. The Ubehebe Peak DEM was imported into a “view window” and displayed as a hill shaded relief map; then the vector (shape) files were added to the view. Since each file is georeferenced, the playa perimeter shape file should have lined up exactly with the terrain data; surprisingly, it did not. The shape files were offset about 200 meters slightly west of north from the position of the digital elevation model (see Figure 6.1). As stated in section 3.10 (page 74) USGS DEMs are referenced using either the North American Datum of 1927 (NAD 27) or the North American Datum of 1983 (NAD 83). The datum used for these DEMs was not specified, but the error appeared as if the datum used in the terrain models was different from that of the GPS data (which was collected using the World Geodetic System of 1984, or *WGS84*).

At first, a rubber sheeting approach was attempted to bring the two data types to the same space, but this method brought with it significant systematic errors and was aban-

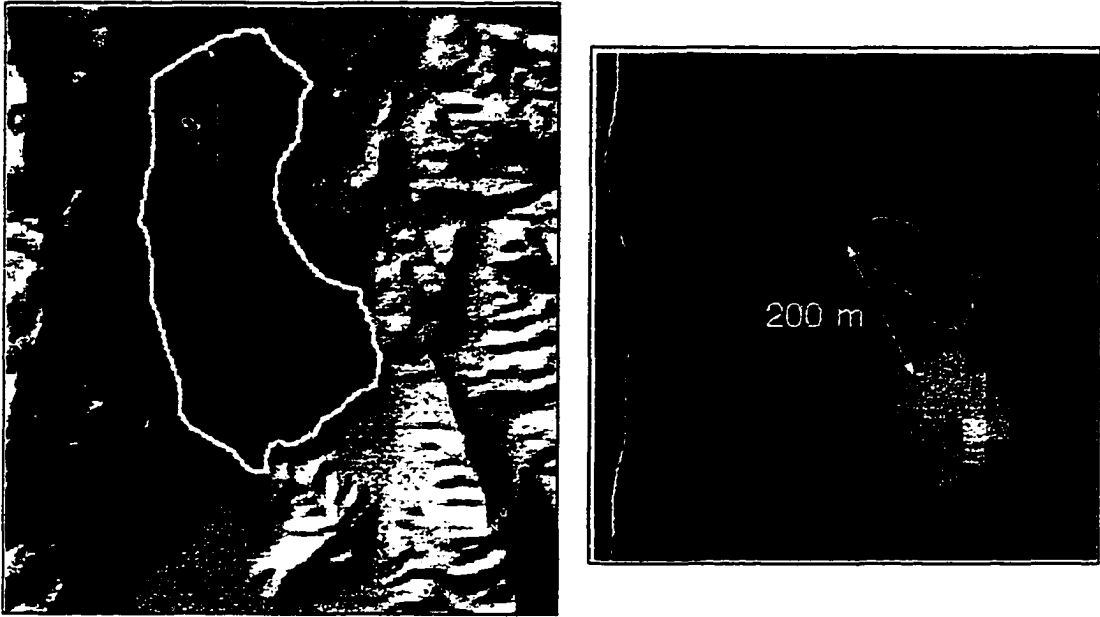


Figure 6.1: Incongruent overlays due to conflicting references. The hill shaded relief map of the Racetrack Playa (left) is based on the 7.5-minute Ubehebe Peak DEM, which is referenced to NAD27. Overlain on this is the GPS vector file of the Racetrack's outline, based on WGS84. Note that the southern boundary of the playa is clearly offset from the topography. The inset outlines the Grandstand; the large scale detail (right) shows that the Grandstand (an easily recognizable feature) was about 200 meters farther northwest in the WGS-referenced data.

done. Perusal of Arc/Info's help screens clarified the problem, and suggested a solution. Using Arc/Info's *Project* function, the Ubehebe Peak DEM was transformed to NAD83, thus shifting the pixels to coincide with the WGS84 vector files. Arc/Info did not have a straightforward transformation application to convert from NAD27 to WGS84, so NAD83 was used instead. NAD83 and WGS84 are virtually identical, both based on the 1980 Geodetic Reference System (GRS80); the more recent DMA-developed WGS84 spheroid carries calculations of the Earth's shape to higher precision (Clarke, 1997). Changing the ellipsoid of the DEM files thus resulted in an accurate overlay of the GPS-mapped data (Figure 6.2).

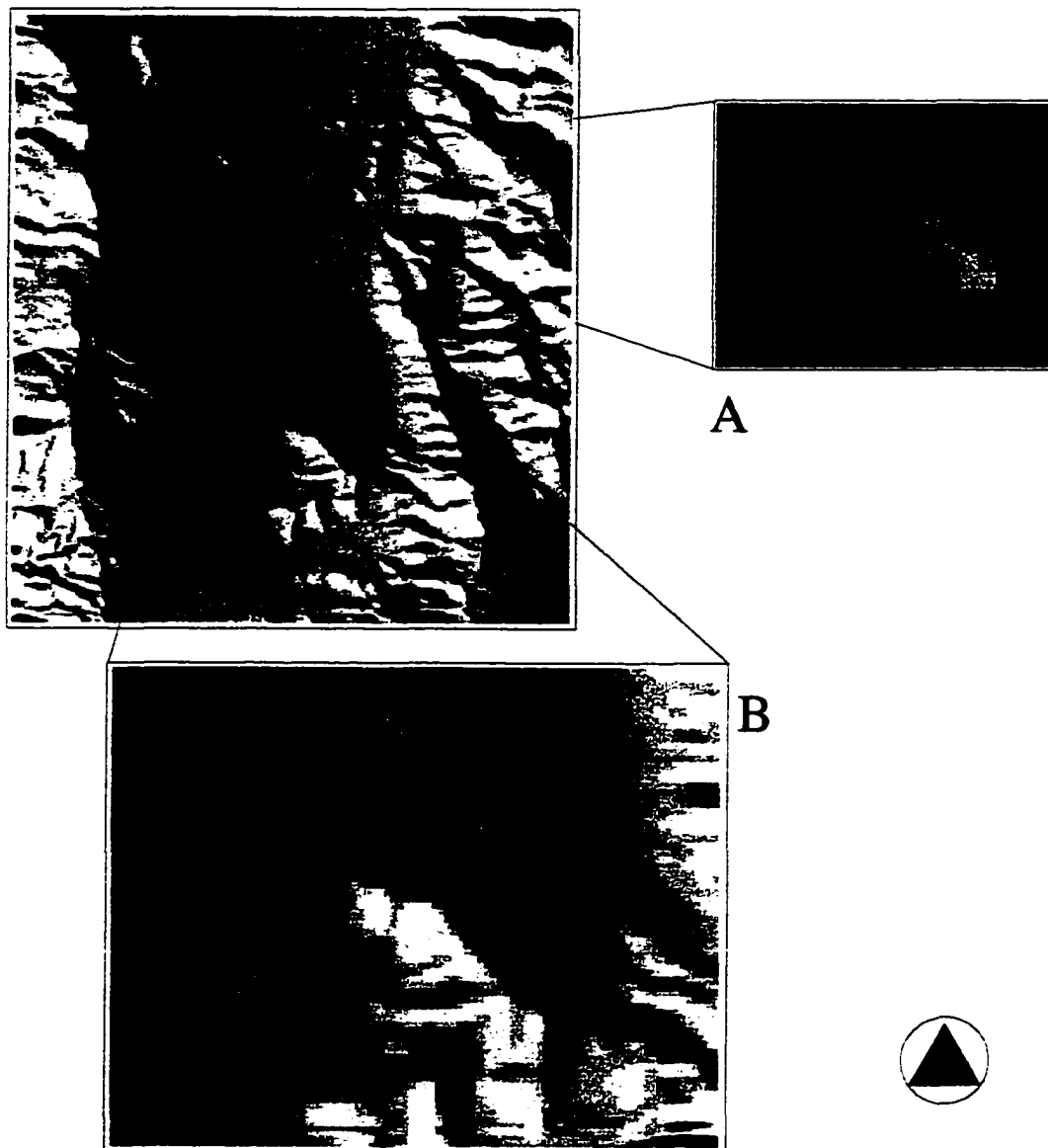


Figure 6.2: Comparison of NAD83 to WGS84. The Ubehebe Peak DEM was referenced to NAD83 (upper left) from NAD27 (Figure 6.1). The Grandstand shape file (white outline, inset A) is aligned with its 30 x 30 meter raster representation. The south end of the playa (inset B) shows congruence with the dolomite cliffs.

6.2 Derived Raster Data

The Ubehebe Peak DEM was used to generate derivative slope and aspect data. Since a digital terrain model is organized as a table whose cells correspond to local elevations, pixel values may be computationally manipulated to yield applied data. A kernel mask considers a small group of pixels at a time, and progressively moves throughout the entire grid until every cell is assigned a value. This value may define the topographic gradient of each 30 x 30 meter element (as in the case of a slope map), or the compass direction of orientation for each 30 x 30 meter element (as in the case of an aspect map). These processes are described (after Burrough, 1986), and illustrated below (see Figure 6.3).

Sample 3x3 array of 100 meter pixels					
Altitude Matrix:	100	130	140	Identifying Kernel:	$Z_{i-1,j+1}$
	120	150	160		$Z_{i,j+1}$
	160	170	200		$Z_{i+1,j+1}$
					$Z_{i-1,j}$
					$Z_{i,j}$
					$Z_{i+1,j}$
					$Z_{i-1,j-1}$
					$Z_{i,j-1}$
					$Z_{i+1,j-1}$

Figure 6.3: A 300 meter square of nine elevation values. This example is used to derive slope and aspect of the central pixel below (Equations 6.1 and 6.2)

To derive the slope of any one pixel, the following equation is used:

$$\text{Tan}G = \sqrt{\left[\frac{(dZ)}{(dX)}\right]^2 + \left[\frac{(dZ)}{(dY)}\right]^2} \quad \text{Equation 6.1}$$

where:

$$[(dZ)/(dX)]_{i,j} = \frac{(Z_{i+1,j+1}) + (2Z_{i+1,j}) + (Z_{i+1,j-1}) - (Z_{i-1,j+1}) + (2Z_{i-1,j}) + (Z_{i-1,j-1})}{8dX}$$

$$[(dZ)/dY]_{i,j} = \frac{(Z_{i-1,j+1}) + (2Z_{i,j+1}) + (Z_{i+1,j+1}) - (Z_{i-1,j-1}) + (2Z_{i,j-1}) + (Z_{i+1,j-1})}{8dY}$$

This is simply an expression of the Pythagorean Theorem. Substituting values to solve for the central pixel in Figure 6.3,

$$\frac{(dZ)}{(dX)} = \frac{[140m + (2)160m + 200m] - [100m + (2)120m + 160m]}{800m} = \frac{160m}{800m} = 0.2$$

and:

$$\frac{(dZ)}{(dY)} = \frac{[100m + (2)130m + 140m] - [160m + (2)170m + 200m]}{800m} = \frac{-200m}{800m} = -0.25$$

Substituting in Equation 6.1:

$$\text{Tan}G = \sqrt{(0.2)^2 + (-0.25)^2} = 0.32$$

so the slope of the central pixel in Figure 6.3 is derived by:

$$\text{ArcTan}(0.32) = 17.75^\circ$$

To calculate the aspect of a pixel, the following equation is used:

$$\text{Tan}A = \frac{(-dZ)/(dY)}{(dZ)/(dX)} \quad \text{Equation 6.2}$$

This equation will yield a value for which the following decision rules must be applied:

- if dZ/dX is negative and dZ/dY is negative: add 90° to the value derived by Eq. 6.2
- if dZ/dX is negative and dZ/dY is positive: subtract 90° from the value derived by Eq. 6.2
- if dZ/dX is positive and dZ/dY is negative: add 270° to the value derived by Eq. 6.2
- if dZ/dX is positive and dZ/dY is positive: subtract 270° from the value derived by Eq. 6.2

So for the central pixel in Figure 6.3, we substitute the following values:

$$Aspect = ArcTanA' \frac{-(-0.25)}{0.2} = 51.34^{\circ}$$

Since dZ/dX is positive, dZ/dY is negative, 270° is added to the outcome shown above to yield a final value of 321.32° . A cursory examination of the subset shown in Figure 6.4 suggests that the central pixel must be sloping towards the northwest since the elevation is lowest (100 meters) in the northwest corner and highest in the southeast (200 meters). When slope and aspect maps are developed by a GIS, these calculations are carried out for *every* pixel in the grid, usually in a matter of seconds. Therefore, for a 1-degree DEM more than 1.44 million separate calculations are conducted for the 1,201 x 1,201 array. The advantages of automated processes are apparent.

A slope map assigns hypsometric tints to inclination classes, thus indicating where on a landscape the terrain is rugged, and where it is flat. Aspect maps code regions by the direction in which each pixel or pixel cluster faces. These calculations are necessary precursors to produce hill shaded relief images, in which reflectivity is inferred by these derived data when combined with an operator-input azimuth and inclination for the sun. Figure 6.4 shows a slope map of the Ubehebe Peak DEM, and Figure 6.5 shows an aspect map of the same data set.

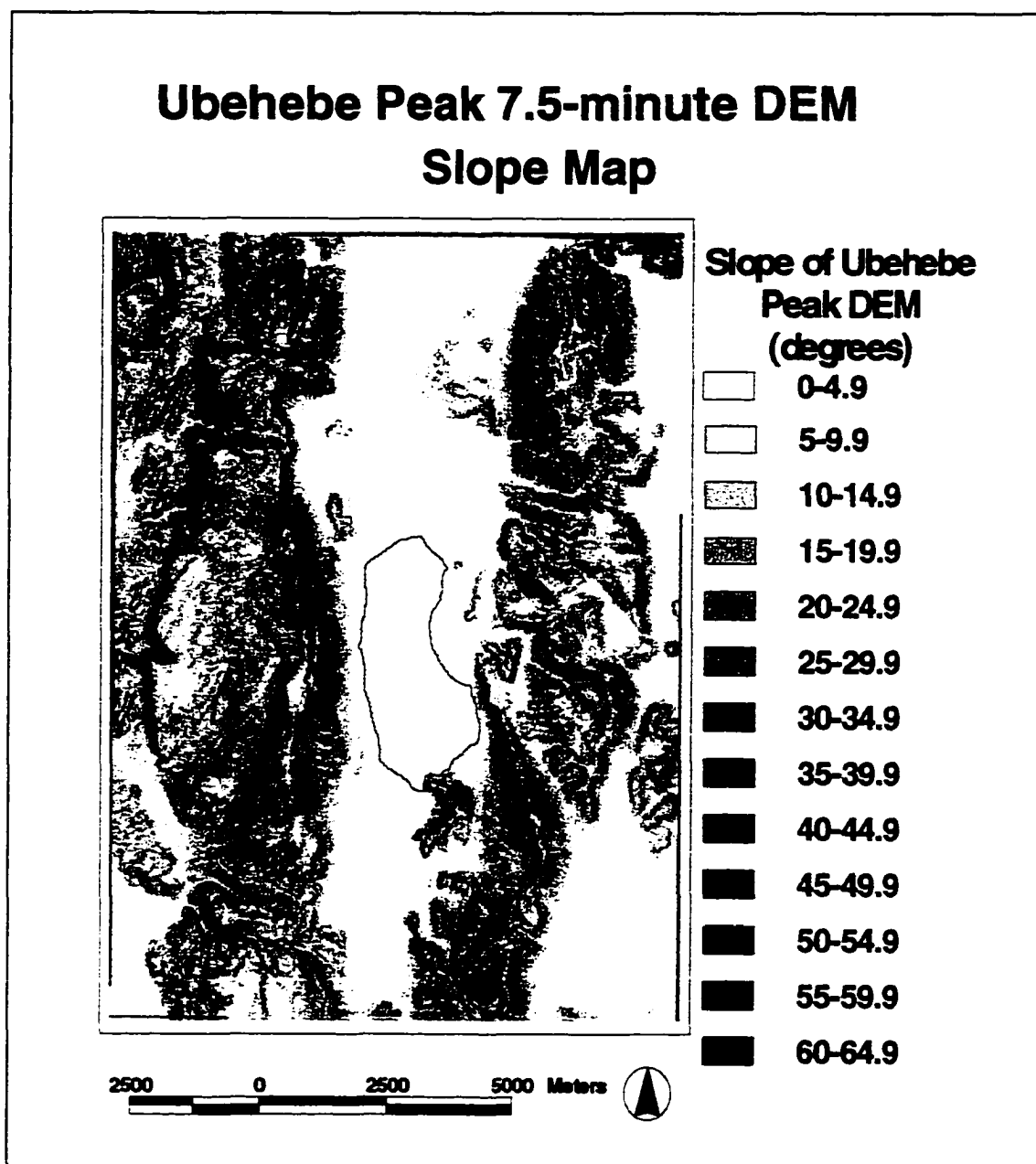


Figure 6.4: Slope Map of Ubehebe Peak quadrangle. Note the Basin and Range topography of generally north-south trending flat areas (controlled by structural faults). Gently-sloping alluvial fans encroach the playa on the north, east and south. This map was constructed with the USGS Ubehebe Peak DEM and ArcView's Spatial Analyst extension. The outline of the Racetrack Playa is the GPS vector data that was collected in July 1996. UTM projection, zone 11.

Ubehebe Peak 7.5-minute DEM Aspect Map

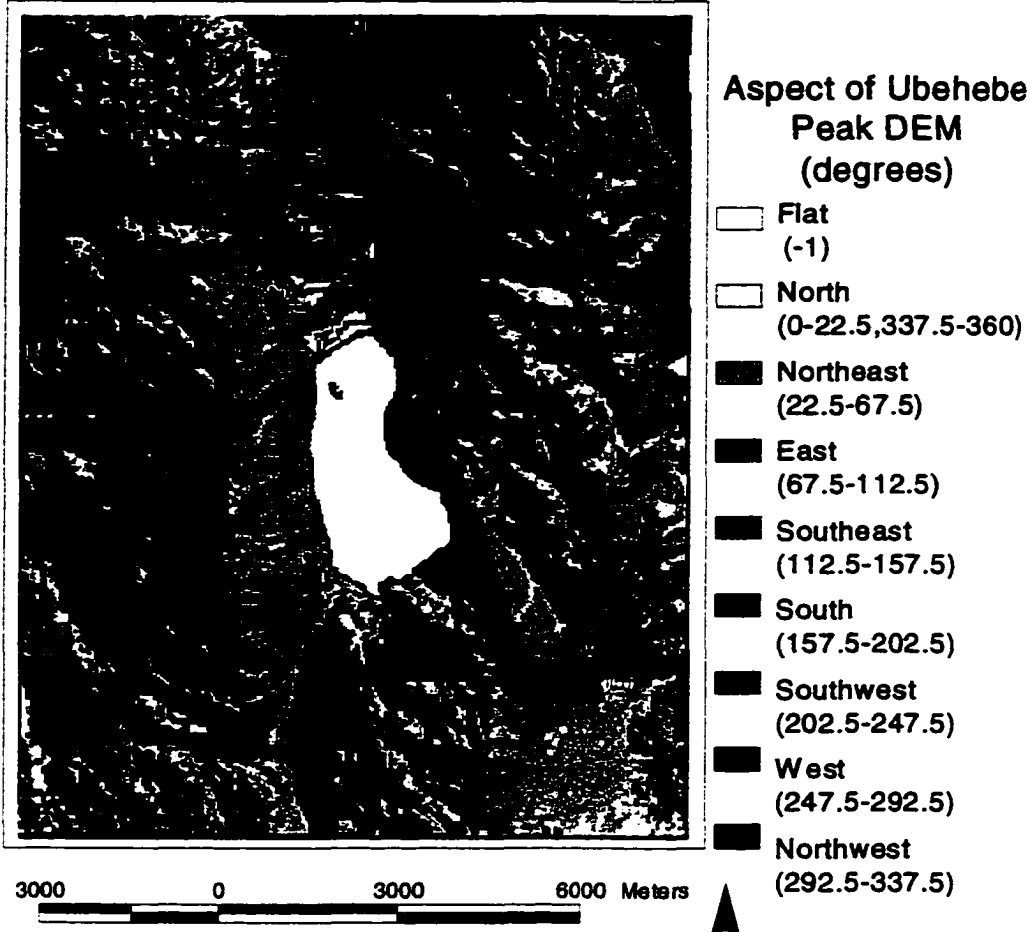


Figure 6.5: Aspect map of the Ubehebe Peak quadrangle. When used in conjunction with Figure 6.5, this map can give the viewer insight into the fault-blocked mountains surrounding flat basins. Although the alluvial fans slope gently onto the playa floor, their slope headings are nonetheless captured by this map.

The map was constructed with the USGS Ubehebe Peak DEM and ArcView's Spatial Analyst extension. The outline of the Racetrack Playa is the GPS vector data that was collected in July 1996. Note the disparity in boundary between the playa polygon and raster data. This is most likely due to the diffuse nature of the northern and eastern borders. UTM projection, zone 11.

6.3 Correlating the Sliding Rock Trails to the Surrounding Terrain

Among the clearest patterns to emerge from the numerical data described in Chapter 5 is the favored trail heading in Octant 0, accounting for over 53% of all cumulative motion. While other correlations were elusive at best, this general tendency for rocks to slide to the north-northeast deserved further consideration. It had been established by Sharp and Carey (1976) that prevailing winds in the area are from the south-southwest, which is consistent with the preferential direction of movement observed in this survey. Yet the existence of such a strong directional propensity may be influenced by the local terrain and microtopography surrounding the lake bed. Figure 6.6 shows a contour map of

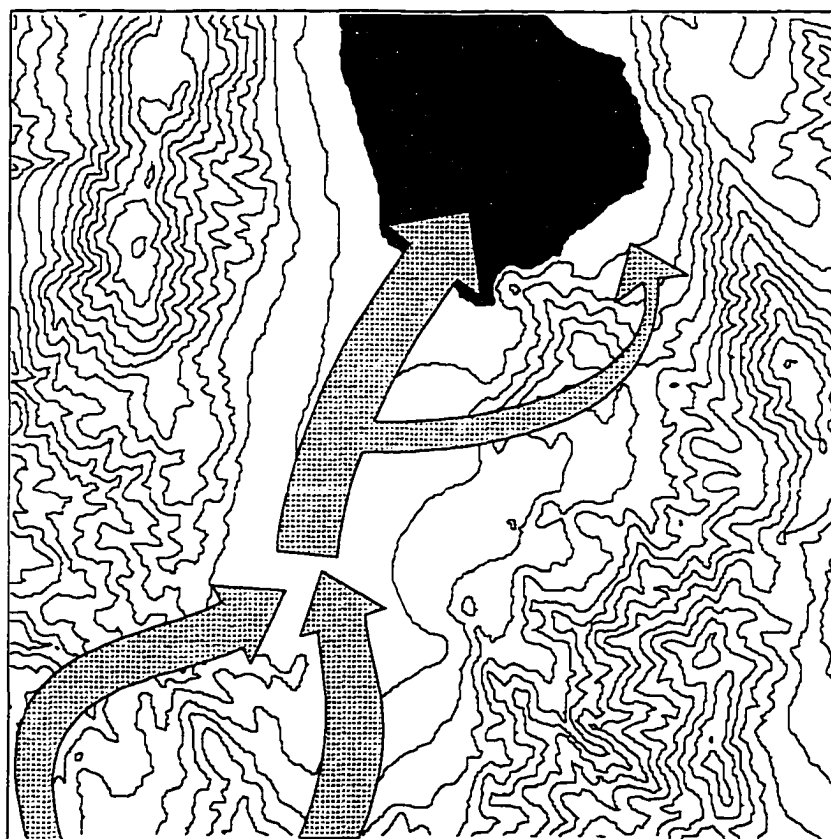


Figure 6.6: Contour map of south end of Ubehebe Peak DEM. Notice the topographic corridors (indicated by gray arrows) to the south of the Race-track. Contours constructed as vector features with a 50-meter interval using ArcView 3.0's Spatial Analyst.

the south end of the playa, highlighting saddles through which air may be channeled and directed onto the playa. Figure 6.7 shows a perspective view of the southwest saddle where two corridors converge, serving to concentrate airflow directly onto the sliding rock field.

There is a high degree of parallelism between the major heading component of most trails and these natural airways. To statistically test the surrounding topography's influence on rock motion, the *aspect* (compass direction of slope orientation) of the local terrain was examined.

6.3.1 Neighborhood Aspect Analysis

The sliding rock field is concentrated at the south end of the Racetrack, so the

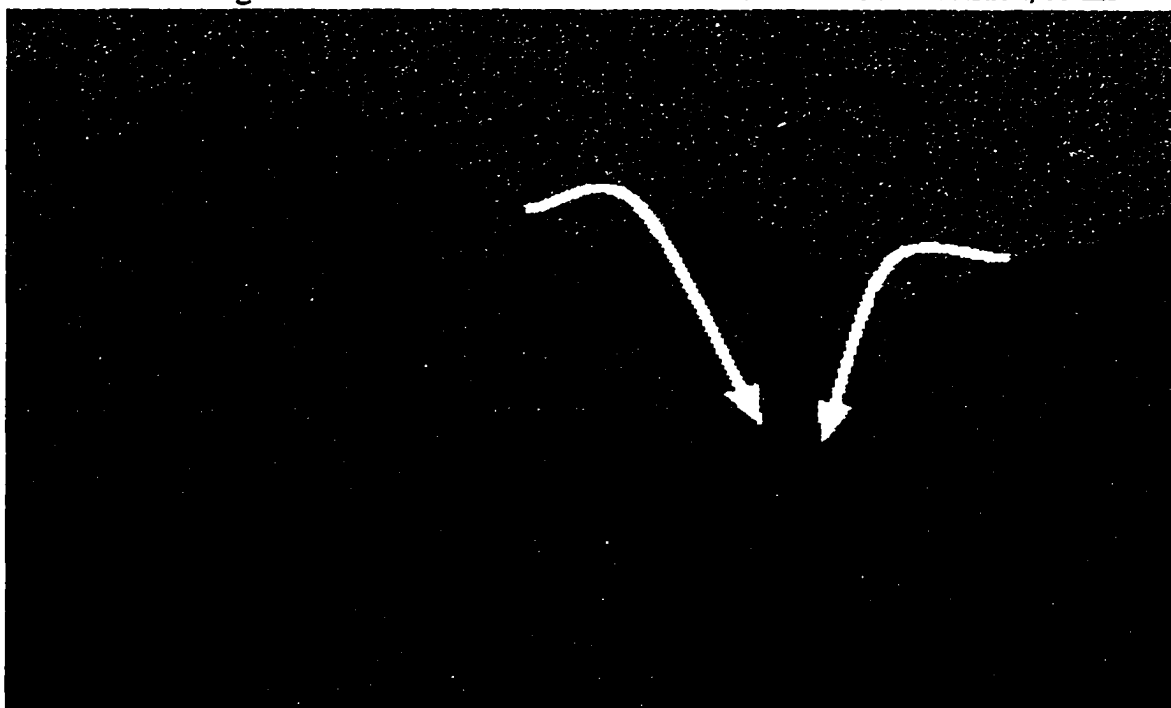


Figure 6.7: Perspective view of the southwest sector of the Racetrack Basin. The two arrows in the extreme southwest corner of Figure 6.7 are shown here as would be seen from the southern playa shoreline. If air is channeled through these saddles, currents converge onto the flat Racetrack floor.

This image is based on the one-degree USGS Death Valley-West DEM, processed as a grid using Arc/Info and imported into ERDAS Imagine version 8.2.

influence of winds may be somewhat limited in scope. Since all rock trails were digitized, each start point was known (see Table G4 in Appendix G); each start point represents a place where air forces exceeded a rock's coefficient of static friction thereby propelling the rock. The zone on the playa that encompassed all start points is a bounding "neighborhood" polygon of every such point in the data set, and is the area on which further studies are based (see Figure 6.8).

To test whether the aspect of the terrain elements within a limited distance from this "neighborhood" polygon had influence over rock motion, a second polygon was constructed with a border 2000 meters from that of the bounding polygon. The extent of this demarcation is illustrated in Figure 6.9. The 2000 meter buffer was used to filter any ter-



Figure 6.8: Bounding polygon of sliding rock start points. The dark gray shape file is superimposed on a hill shaded relief image of Racetrack Basin. White dots indicate trail origin points.

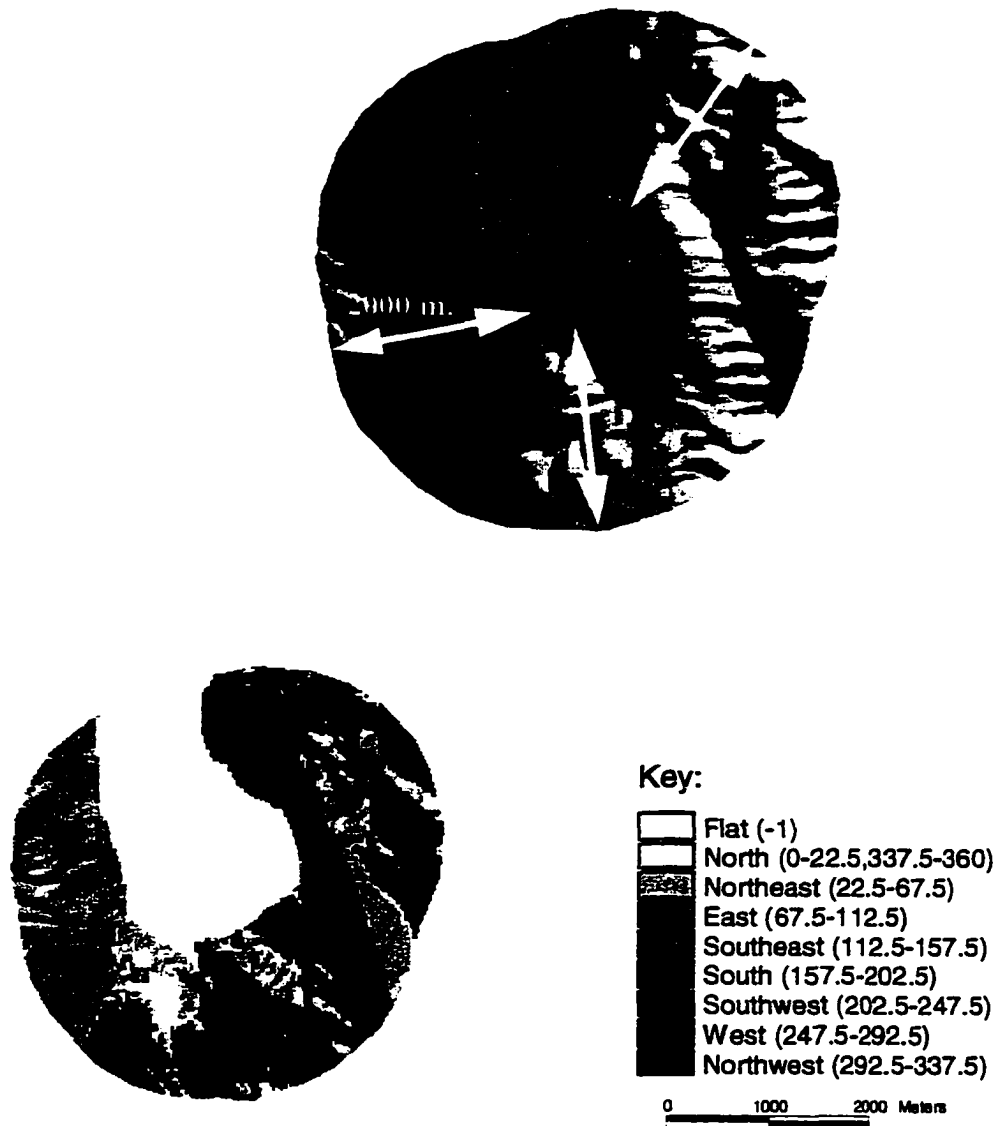


Figure 6.9: Buffer zone surrounding the bounding polygon. The hillshaded relief image (top) shows the extent of the elevation data included in visibility analyses (see section 6.32). The aspect map (bottom) shows the same buffer zone; this time the pixels are coded for azimuth of inclination.

rain data beyond that distance from the rock field. Once the DEM was filtered, an aspect data set was created from this subset. The resultant “clipped” aspect map was the base map for the next phase of analysis.

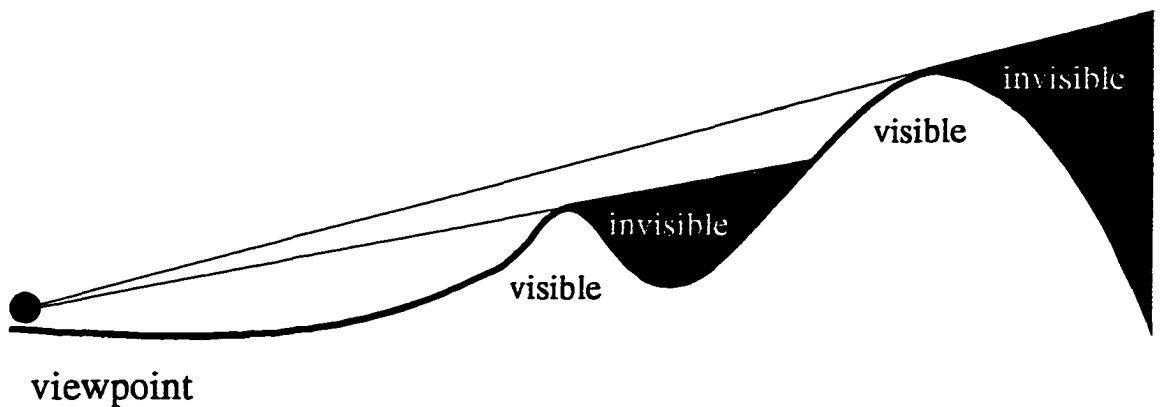


Figure 6.11: Intervisibility using ray tracing. (After Clarke, 1995)

6.3.2 Viewshed Analyses

The rocks at Racetrack Playa lie on a flat plane, but are surrounded by intricate landforms. Air is forced through natural channels, but each rock may be subject to slight differences in wind velocity based on its location relative to the fringing topography.

Given a digital cartographic representation of a terrain surface and a single point on the surface, the set of regions that are visible from that point describe *intervisibility* (Clarke, 1995). Intervisibility is determined by a method known as *ray tracing*, and is illustrated in Figure 6.11. The *viewshed*, or 360° panorama of the visible terrain around each rock is a function of its placement and height above the surface. On a perfectly flat terrain, a viewshed would extend to the visible horizon in all directions. Any substantial relief such as a mountain acts as a barrier to the panorama, and also as a shield to air currents at shorter ranges. Processing viewsheds for representative rocks could establish the existence of significant variations in the terrain in the neighboring buffer zone, and hence associated airflow potentials.

For this study, the start points of twelve rocks were selected. The subset of rocks

was chosen based on several criteria: spatial distribution on the playa; representation of a range of trail straightness ratios; representation of a range of trail lengths; representation of a range of rock sizes. Selection rationalization for each rock is listed in Table 6.1.

Table 6.1: Twelve-rock Visibility Subset Selection Criteria

Rock Number/Name	UTM Coordinates of Start Point		Rationale
	Easting (X)	Northing (Y)	
031 Jacki	450131.0	4057974.5	Although starting nearly 37 meters apart on the playa, these trails end in highly parallel “scribbles.”
032 Amelia	450099.9	4057956.3	
045 Karen	450025.4	4058639.4	One of the three largest rocks; situated at the northwestern neighborhood limit.
050 Alice	450235.0	4058450.5	The second most crooked trail (0.271 straightness quotient).
063 Marietta	450215.9	4057719.6	The most southerly start point.
069 Sandra	450013.9	4057625.9	An extreme southwesterly start point.
073 Claudia	450125.1	4058042.0	The most crooked trail (0.187 straightness quotient).
080 Sheryl	450199.6	4057998.8	The straightest trails of appreciable length* (0.997 straightness quotient).
084 Josephine	450237.5	4057784.0	
140 Debbie	450726.8	4058005.2	An extreme southeasterly start point.
141 April	450953.3	4058866.9	The most northeasterly start point.
145 Diane	450444.5	4057957.6	The longest trail (881 meters).

*139 Agnes is the straightest trail, but it measures only 6 meters in length. As a result, 080 Sheryl and 084 Josephine (with trail lengths of 26 and 84 meters, respectively) were included instead.

Each of the twelve trail origin points were saved as point coverages using Arc/Info *generate*. Point files were cleaned and projected to UTM. The Ubehebe Peak DEM was

cropped using the Arc command *latticeclip*: the polygon coverage of the 2000-meter buffer zone acted as a “cookie cutter.” The resulting DEM extended 2000 meters beyond the limit of the bounding polygon in all directions, and was named <clipdem>.

Using each of the twelve point coverages individually, the Arc command *visibility* computed the 360° viewshed for each start point. The usage for this command, using Amelia as an example is:

visibility <clipdem> <amelia-point> point <amelia-view> grid

where:

- <clipdem> is the 2000-meter buffer cropped DEM-derived aspect map,
- <amelia-point> is the point coverage of Amelia’s origin,
- “point” specifies that the viewshed will be based on one point (as opposed to a line),
- <amelia-view> is the name of the viewshed grid file generated,
- “grid” specifies that the output file is a raster grid.

It should be noted that this process is computationally intensive and quite time-consuming.

When the grids were output to ArcView their associated data base files were exported to Excel. The original clipped DEM encompassing the 2000-meter buffer zone contained 22,749 30x30-meter pixels. Since this value was known, as were the total number of visible pixels in each rock’s viewshed, the “visibility ratio” of each rock was computed. The quotient of the rock’s visible pixels to the total number of pixels in the buffered grid describes the relative intervisibility for that rock *before* it started moving. Table 6.2 shows the relative viewsheds for the twelve representative rocks.

Table 6.2: Number of Pixels Visible/Invisible to Twelve Representative Rocks

Rock Name/ Number	Number of Pixels Visible	Number of Pixels Invisible	Visibility Quotient
Alice 050	15205	7544	.6684
Amelia 032	14595	8154	.6416
April 141	13354	9395	.5870
Claudia 073	14727	8022	.6474
Debbie 140	16406	6343	.7212
Diane 145	13515	9234	.5941
Jacki 031	14517	8232	.6381
Josephine 084	13036	9713	.5730
Karen 045	15834	6915	.6960
Marietta 063	11972	10777	.5263
Sandra 069	12452	10297	.5474
Sheryl 080	14339	8410	.6303

As is evident in Figure 6.11, the rocks selected for the visibility studies describe an approximately normal distribution of visibility profiles. A cursory analysis of Table 6.2 shows that the longest trail (Diane) had one of the smallest number of visible viewshed pixels at its start point. Given this possible link to total intervisibility area and trail character, several regression analyses were implemented. The results of those scatter plots are presented in Table 6.3.

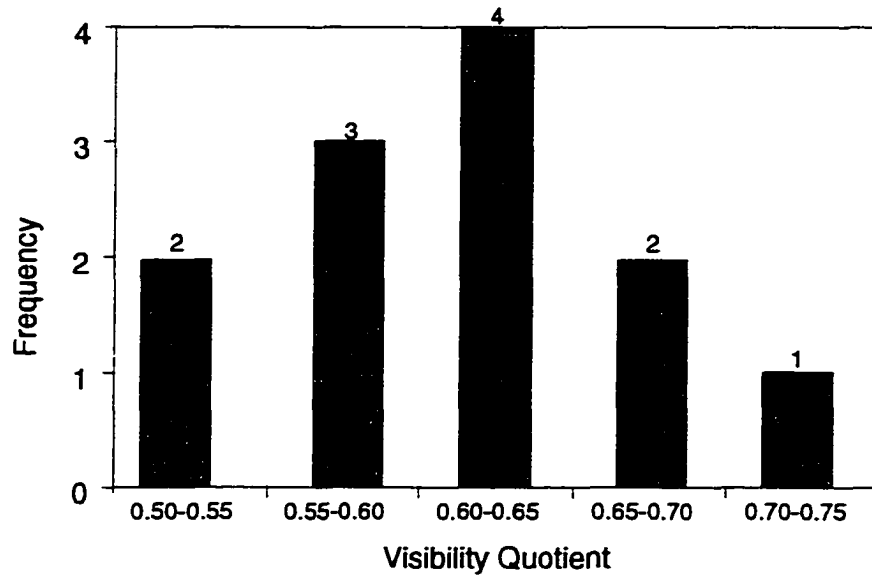


Figure 6.11: Frequency distribution of visibility quotients for representative rocks.

Table 6.3: Results of Selected Visibility-Related Regression Analyses

X variable	Y variable	Relationship (+ = direct; - = inverse)	Correlation Coefficient (r^2)
Number of Total Visible Pixels in Viewshed	Straightness Quotient of Trail	-	0.1679
	Distance to Springs of Trail Start Point	-	0.0842
	Direct Trail Length	-	0.0135
	Total Trail Length	+	0.0061

Relationships between trail character parameters and number of viewshed pixels were weak. However, the analyses above weighted all visible pixels equally. Since the goal of this study was to associate qualities of trails with the surrounding terrain, further intervisibility area details were needed. An aspect analysis of the DEM subset <clipdem> was generated, and named <clip-asp>. The twelve raster files resulting from the visibility

analysis function (see “*visibility* <clipdem> . . .” on page 182) were converted to polygons using Arc’s *gridpoly* function. All twelve coverages were named <rockname-cov>, projected to UTM, and then cleaned. These coverages were in turn used as “cookie cutters” on the cropped aspect map, “clipasp.” The command for Amelia, for example was:

latticeclip <clip-asp> <amelia-cov> <amelia-vis>

where:

- <clip-asp> is the grid of aspect-coded pixels to be cropped,
- <amelia-cov> is the viewshed polygon,
- <amelia-vis> is the output viewshed grid

The resulting twelve rocks’ “-vis” grids were raster files of the aspect of every visible pixel in that rock’s viewshed, before it started moving to its current location.

The tabular data from these manipulations were exported to Microsoft Excel. The spreadsheets, as exported by ArcView, consisted of two columns, one for the compass heading and the other for the total number of pixels in the viewshed with that orientation for each rock. There were up to 361 rows for each rock, one row for the flat pixels in the viewshed (labeled “-1°”), and one row and associated number of pixels for each compass heading (1° to 360°).

Once the spreadsheet was constructed, pixels were “clumped” into eight groups to match the octant categories already defined. Table 6.4 shows the summation limits.

Table 6.4: Aspect Designation by Octant

	Octants							
	0	1	2	3	4	5	6	7
Inclusive Headings	1-45	46-90	91-135	136-180	181-225	226-270	271-315	316-360

The data were summed further to produce groups of the four cardinal compass directions, and again to those offset by 45°. Table 6.5 shows these distributions.

Table 6.5: Aspect Designation by Quadrant

	Quadrants							
	N	E	S	W	NE	SE	SW	NW
Inclusive Headings	1-45; 316-360	96-135	136-225	226-315	1-90	91-180	181-270	271-360

A summary of the total number of visible pixels by Octant (Table 6.5) follows.

Table 6.5: Number of Visible Pixels in Viewshed of Rock, by Octant

Rock Name/ Number	Octants								Total Inclined Pixels	Flat Pixels	Total Pixels in Viewshed
	0	1	2	3	4	5	6	7			
Alice 050	857	2086	1612	324	515	1562	1575	1269	9800	5405	15205
Amelia 032	717	2054	1602	333	495	1633	1402	954	9190	5405	14595
April 141	746	2155	1616	300	381	932	1137	884	8151	5203	13354
Claudia 73	740	2059	1604	332	496	1623	1422	1041	9317	5410	14727
Debbie 140	898	2089	1489	354	621	1939	2142	1443	10975	5431	16406
Diane 145	620	2083	1602	317	431	1273	1176	710	8212	5303	13515
Jacki 31	720	2056	1600	331	488	1618	1367	935	9115	5402	14517
Jose- phine 84	510	2036	1589	325	458	1372	955	445	7690	5346	13036
Karen 45	873	2090	1526	321	566	1750	1898	1387	10411	5423	15834
Marietta 63	363	1988	1540	318	436	1207	720	177	6749	5223	11972
Sandra 69	492	1919	1532	322	464	1375	714	378	7196	5256	12452
Sheryl 80	714	2055	1601	331	482	1525	1316	922	8946	5393	14339

The pixel counts for octants were added together defining viewsheds by quadrant, as follows:

- Σ pixels in Octants 7 + 0 describe visible North-facing slopes,
- Σ pixels in Octants 1 + 2 describe visible East-facing slopes,
- Σ pixels in Octants 3 + 4 describe visible South-facing slopes,
- Σ pixels in Octants 5 + 6 describe visible West-facing slopes,
- Σ pixels in Octants 0 + 1 describe visible Northeast-facing slopes,
- Σ pixels in Octants 2 + 3 describe visible Southeast-facing slopes,
- Σ pixels in Octants 4 + 5 describe visible Southwest-facing slopes,
- Σ pixels in Octants 6 + 7 describe visible Northwest-facing slopes.

These totals may be found in Tables H1 and H2 in Appendix H.

6.3.3 Trail Heading Correlations to Surrounding Visible Topography

Motion of the rocks is inferred by the pattern of their trails: Table G5 in Appendix G lists motion by octants; Table G6 in Appendix G lists the percentages of a rock's route in each octant. As noted by Figures 5.27 (page 152) and 5.28 (page 152) the greatest directional component for the majority of trails was in Octant 0 (north-northeast). When a similar analysis is conducted on the representative samples' visible pixel aspects, it is evident that the heading of surrounding terrain elements are not random and are related to the design of the trails. Table H3 in Appendix H shows the percentage of visible pixels per octant and per quadrant of each of the rocks, excluding the flat terrain. Figure 6.12 shows the viewshed means for all rocks.

For the twelve representative rocks, percentages of direction components per trail and orientation of pixel elements per viewshed were calculated, by quadrant. Table H4 in Appendix H shows the complete data for individual trails and viewsheds. These data were then averaged by quadrant (Table 6.6). A comparison of the sampled rocks' mean trail segment headings to their visible pixel aspects shows some interesting patterns.

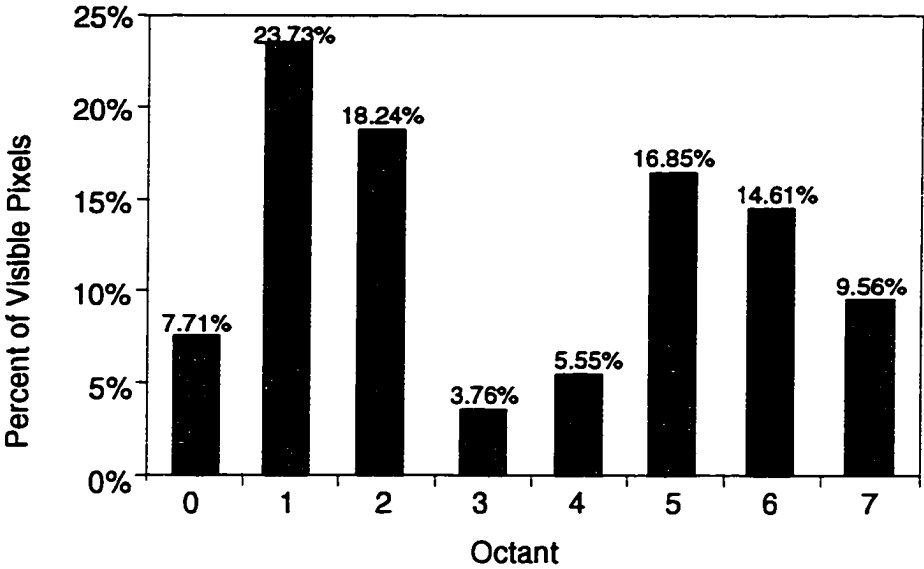


Figure 6.12: Mean percentage of aspects visible to representative rocks, by octant.

Table 6.6: Pixel Aspect Means for Sampled Rocks’ Viewsheds and Corresponding Trail Heading Means, by Quadrant

	North	East	South	West
Aspect of Viewshed Pixels	17.26%	41.97%	9.31%	31.46%
Trail Heading Components	66.36%	6.38%	10.92%	16.34%

	Northeast	Southeast	Southwest	Northwest
Aspect of Viewshed Pixels	31.44%	22.00%	22.40%	24.17%
Trail Heading Components	44.41%	13.41%	2.97%	39.22%

There is a noticeable inverse relationship between aspect of viewsheds and trail headings. Particularly in the cardinal directions (top) Table 6.6 shows that high values in a particular quadrant for pixel aspects corresponded to low values for trail headings, and vice versa. The relationship in the offset quadrants (bottom) are more diffuse.

When percentages for complementing quadrants are summed and compared, the results suggest a significant relationship between trail character and terrain. Figure 6.13 shows the correspondence.

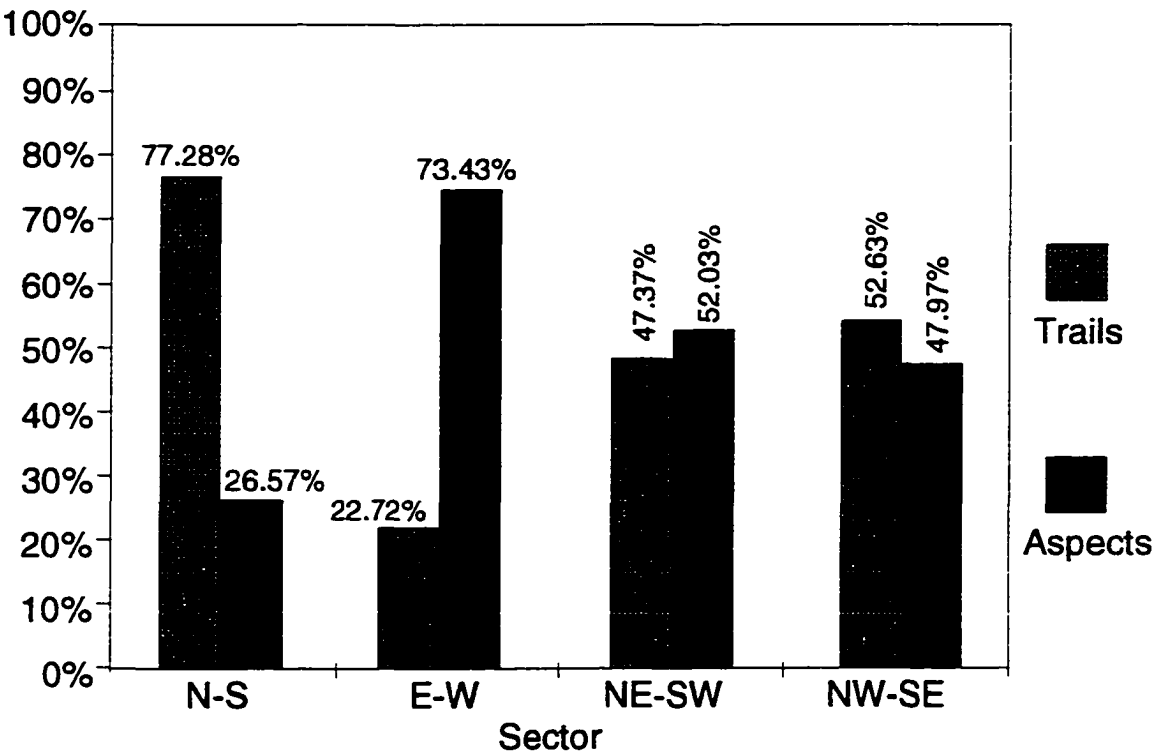


Figure 6.13: Comparison of pixel aspects to trail component headings for averages of twelve representative rocks.

The trails show a directional preference to the quadrants *orthogonal* to the majority of the pixel aspects' orientations. In other words, a preponderance of east- or west- facing slopes appears to be correlated with the general north-south plans of the trails. This is particularly evident of north-south, east-west correlations in Figure 6.13.

To check the interdependence of trails to their surrounding orthogonal terrain elements t-Tests were conducted. Tests on whether the paired data support a null hypothesis (i.e., there is *no* relationship between the trails' directions and orientation of the surrounding slopes) allowed the null hypothesis to be rejected at the 95% confidence level ($\alpha=0.05$). The results of two such comparisons are shown in Table 6.7.

Table 6.7: Results of t-Tests for Terrain-Trail Paired Data

	NE-SW Trails	NW-SE Terrain	N-S Trails	E-W Terrain
Mean	51.76	46.16	78.95	73.43
Variance	1344.38	8.99	819.88	11.96
Observations	12	12	12	12
Pearson Correlation	0.117		-0.550	
Hypothesized Mean Difference	0		0	
df	11		11	
t Stat	0.532		0.624	
P(T<=t) one-tail	0.303		0.273	
t Critical one-tail	1.796		1.796	
P(T<=t) two-tail	0.605		0.545	
t Critical two-tail	2.201		2.201	

Hence the establishment of a valid positive relationship between the viewsheds' slopes and dissected trail components shows that rock movement on the playa can be correlated to the orientation of the flanking corridors. It is likely that these chutes act as natural wind tunnels, directing airflow onto the playa surface.

Chapter 7

Discussion

The first GPS-based sliding rock map generated by this survey adds some evidence to the enigmatic system of sliding rocks, particularly when considered within the context of the surrounding terrain. Inferences about the physical characteristics of the playa surface when motion occurs, possible motive mechanisms, and the influence of the bordering topography on wind events are discussed below.

7.1 Prevalence

The sliding rock phenomenon is a complex, but not uncommon process. As noted earlier, Sharp and Carey (1976) published an inventory of playas in the Southwest showing similar recorded events (see “Table 4.2: Playas in Southeastern California and Adjacent Nevada Displaying Stone Tracks” on page 98). Among the only other published accounts are those of dry lakes in Tunisia (DiCesare and Pratelli, 1967). What may make the Racetrack unique is the superior preservation conditions attributed to its isolation and national park status. Yet the presence of almost any massive natural material several hundred meters from the boundary on any flat playa may indicate sliding rock activity.

If trails are eradicated by anthropogenic or natural processes, then one may not even question their anomalous positions. If tires, *washing machines* (see page 106), and

other voluminous human refuse litter similar playas, their origins are clear. But the placement of a stray boulder found in a similar location may not be challenged. Clements (1952) questioned the occurrence of this surface process; Motts (1970) surmised that it is fairly common among similar surfaces (see quote, page 97).

Personal observations of a sliding rock trail on Little Bonnie Claire Playa (see Figure 4.16, page 101) and numerous loose rocks scattered on Panamint and Nelson playas suggest the universality of the phenomenon.

7.2 Playa Surface Environment

One of the hypotheses strongly suggested by the nature of the furrows is that the surface of the playa is wet when motion occurs. If it were possible for rocks to move at other times, the trails would appear more like rough scrapes. Many rocks leave trails with a “wake-like appearance,” and a few of the larger ones (e.g. “Kitty”) leave splash marks in the muds behind them. The saturation is limited in vertical extent, affecting the uppermost playa crusts; a very firm silty substrate prevents rocks from sinking in. Hence there is general agreement that the lake bed is quite slippery and wet when the rocks move.

7.2.1 Racetrack Sediments

The current source of the playa’s deposits are the alluvial fans that surround it. With the exception of the west border where sediment supply has been intercepted by the bounding ditch, the vast majority of particles reach the Racetrack as the results of mass wasting processes.

The Racetrack’s deposits are fine-grained (Motts, 1970), specifically: 24% fine sand, 41% silt and 35% clay (Sharp and Carey, 1976). It was suggested by Creutz (1962,

see page 38) that the playa deposits themselves were solely responsible for the sliding rocks' actions. If clays on this playa were to swell appreciably upon saturation as surmised by Creutz, then it would be conceivable for some activity to take place as a result. However, Sharp and Carey (1976) noted that this playa has a lower montmorillonite fraction and higher illite component than other Mojave playas. Hence the thixotropic behavior of clays here would be minimized. Creutz's hypothesis, while interesting, is not well-founded in this locality.

When the surface of the playa is wetted, particles mix with the water to varying degrees forming a turbid liquid. This mixture can then move in sheets propelled by the wind (ultimately producing the lobate deposits illustrated in Figures 4.8 [page 92], 4.9 [page 93] and 4.17 [page 102], or stay in place. The suspension of the smallest clay fraction is most likely responsible for unparalleled surface slickness, as hypothesized by Sharp and Carey (1976 and 1996). Studies aimed at measuring coefficients of friction on artificially wet playa surfaces (i.e., Sharp, 1956 and Reid et al., 1995) were possibly flawed in that in an effort to realistically expedite their experiments the filmy residue of finest clays were not allowed to form. It is likely that the thin brown veneer (observable mostly as the deflated collections of mud curls at the playa's periphery) is a necessary component for rock movement. Section "7.2.2 Cyanobacteria" on page 196 adds the role of biogenic activity to enhance the slickness even further. Under the fine uppermost clay lies a substrate of silt and fine sand, responsible for the characteristic polygons that form following saturation and subsequent desiccation.

While Reid et al. (1995) reported that the value they measured for the playa's coefficient of friction (μ) was surprisingly high (0.8), they refrained from elaborating on their

methodology. The paper stated that the playa surface was wetted by artificial means, but it does not describe how the value for μ was computed. Death Valley's Resources Management Division (the department granting and monitoring research permits) was queried, yet they had little information about how Reid et al., came upon that quantity (Richard Anderson, 1996, personal communication). It is assumed that a boulder was dragged across the playa surface; its static friction coefficient may have been computed as the force required for initiation of movement, and its dynamic friction coefficient may have been calculated as the force needed to sustain motion using a spring. But the description of the selected boulder simply as a "12 kg. angular dolomite" (Reid et al., 1995) leaves some inferences to the reader. While most sliding rocks surveyed in this project could have been categorized similarly, no details were given as to the nature of its shape irregularity. Furthermore, the surface of contact chosen by the group would certainly have influenced their results.

Most importantly, fresh clays from encroaching alluvial fans were not introduced into this experiment, as would have occurred under natural wetting events. In their description, the group reported that they allowed the upper playa surface to soften for approximately two hours after wetting it down. However, even if fine clays were initially present, formation of the slick veneer would require a longer time interval.

The clays themselves show evidence of entrainment in moving bodies of mud (see Figure 4.8, page 92 and Figure 4.9, page 93). These projections of viscous material scar the Racetrack's surface in features that sometimes resemble giant bar codes (Figure 7.1). The lineations sometimes cross others, at near-90° angles, forming a cross-hatch-like pattern running southwest-northeast and southeast-northwest, particularly near the northern extent of the sliding rock field. These patterns lie parallel to two dominant wind corridors

at the south end of the playa.

These “sliding glops” are apparently propelled by wind, and may at times become airborne as evidenced by isolated and unattached deposits of material forming small detached piles. The movement of these fluid bodies is probably similar to that of wind-blown foam mixtures of sand and sea water on coastal beaches. The turbid clay-water mixture probably moves slowly due to fluid cohesion, leaving a record of its farthest extent in the form of low mud mounds.

7.2.2 Cyanobacteria

The slickness of the uppermost coating may be enhanced by the presence and periodic rejuvenation of cyanobacteria. Shelton (1953) noted that a tissue paper-like film was peeled off some tracks, especially where rocks may have rested for a while (termed “sitz



Figure 7.1: Scars of mud curls form orthogonal patterns in the central playa region. These patterns are congruent with the topographic corridors at the playa's south end.

marks” by Sharp and Carey, 1976). A laboratory assistant discovered that this “pond paper” was produced in part by cyanobacteria, *Microcoleus* sp., whose filaments produce a homogeneous sheath of an extremely gelatinous nature (Shelton, 1953). This material may be an important lubricant; furthermore, as a biological agent requiring time to bloom, its effects would not be detectable immediately after a wetting event. Figure 7.2 (page 198) shows areas of cyanobacterial proliferation as observed in December 1996.

7.2.3 Water Sources

It is agreed among researchers that water, either as a liquid or solid, must be present before any activity may occur. While most have interpreted that to mean that local *rainfall* is a requirement, the possibility of other natural sources of water have been overlooked.

As mentioned in sections “4.2.3 Hydrologic Features” on page 87 and “4.5.2 Hydrologic Features” on page 123, three well-developed depressions on the eastern edge of the Racetrack were filled with water during three of the four visits to them in 1996-1997. Empty only in February 1996, these pits contained water in July, 1996; December, 1996; and March, 1997 despite low rain totals in 1996 and early 1997. Figure 7.2 shows the largest pool as it appeared in December, 1996 (compare this image to Figure 4.22 on page 116, taken five months earlier when the maximum extent of water was observed). This early winter visit resulted in the first positively-identified spring as water was observed upwelling into the largest pool. Although production was visually noted, it was not measured as per national park regulations. The flow appeared sluggish, and could easily have been counteracted by evapotranspiration given the high general insolation rates and number of salt bush anchored nearby.

It seems plausible that these pools may experience a state of dynamic equilibrium at times when input and loss rates are equal, however, input may be enhanced by regional groundwater recharge and may not be attributed *only* to local precipitation. The position of these ponds (see Figure 4.7, page 91, and Figures 7.3 and 7.4 below) in a relatively straight line may signal subsurface faults or joints through which subterranean water sources may be contributors.

Seismic studies conducted in March, 1997 by Alexis Moiseyev and Detlef Warnke of California State University, Hayward showed a shallow, level reflective plane near the springs, but the results of these studies are inconclusive.

The presence of brine shrimp (observed in July, 1996), animal tracks and well-established vegetation surrounding the springs are testaments to the persistence of these features. Large fissures that parallel the general trend of the greater fault lineament

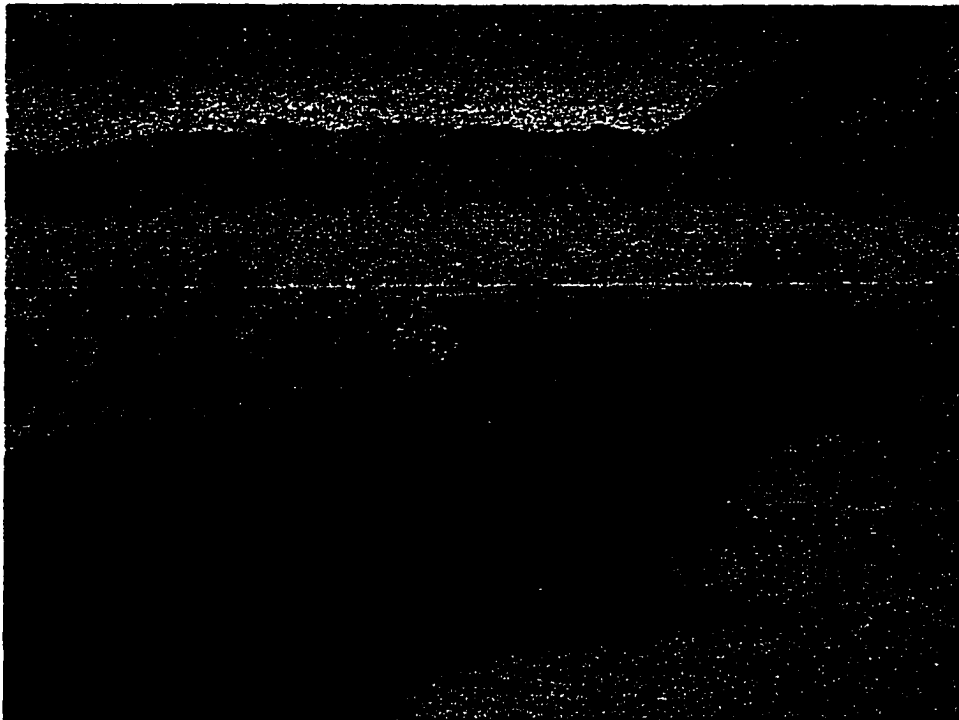


Figure 7.2: Largest of three spring-fed pools, December 1996. Note the small white bird at its center, and algal blooms along the closer margins.

recessed into the hard pan in the spring area suggest that neotectonic activity is a continuing and contributory process.

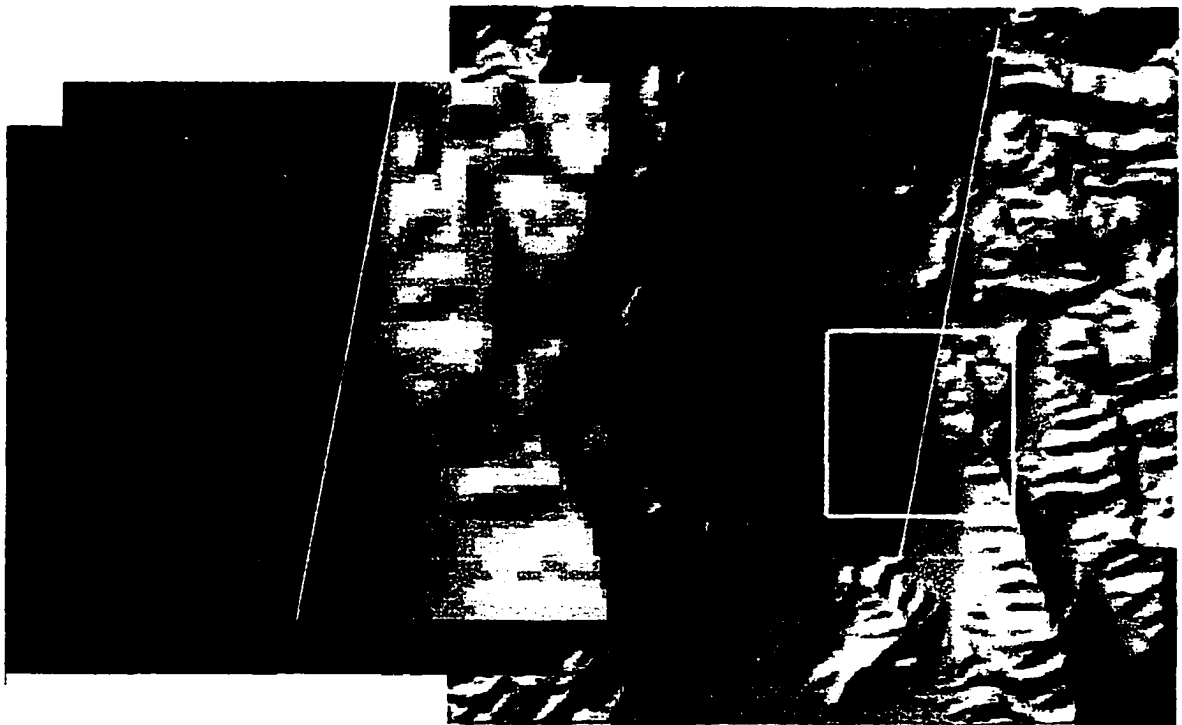


Figure 7.3: Location and orientation of three playa springs, within topographic context. Water infiltrates subterranean faults via ephemeral streams to supply these source areas. The inset (left) shows an enlargement of the eastern edge of the Racetrack and the surrounding terrain (right). This hillshaded relief image highlights the existence of scarps with similar orientation to the general strike of the depressions. Compare this map-view to the digital image in Figure 7.4 (next page).



Figure 7.4: Pool of turbid water and incised drainage pattern: December, 1996. Note how this pool and one in the distance (indicated by the presence of a far patch of salt bush) are aligned with the dark slope, a possible fault- or joint-controlled scarp.

The dendritic water-carved feature is quite similar in function to a tidal channel, allowing water to flow both away from the spring at times of flooding, and towards it when the water table falls.

7.3 Atmospheric Boundary Layer

As described by Bacon, Cahill and Tombrello (1996), Owens Lake was found to have a remarkably steep vertical wind gradient, with maximum wind speeds perhaps just a few centimeters above its surface. In response to that research Reid, Polissar and Williams (1996) argued that the boundary layer on nearby Panamint Playa showed no similar vertical compression, citing that wind speeds 5 centimeters above the dry lake were only 50% of values at a height of 1.5 meters.

However, using Panamint Lake as an analog to the Racetrack is unfounded for several reasons. First, the Racetrack Playa is about 550 meters *higher* in altitude than Panamint Valley. When air moves from Saline Valley up through the southwest topographic corridor into the Racetrack Basin, it climbs over 500 meters. Although the vertical extent of the troposphere is somewhat influenced by underlying topography, its upper limits do not parallel surface landforms to any degree of precision (Barry, 1992). Instead, the layer of air thickens and thins as it moves over areas of relief. As air moves from low- to high-altitude areas there is a vertical deflection and compression of streamlines resulting in increased wind speeds. To contrast, Panamint Valley is a virtually flat north-south-striking basin, tens of kilometers long and nearly 10 kilometers wide. Prevailing winds flowing up this valley remain at a fairly steady altitude, with little horizontal or vertical compression necessary. The Racetrack is not only higher (and therefore subject to a vertical airflow compression), but it is much narrower than Saline Valley downwind, making it susceptible to horizontal airflow compression as well. Hence, by virtue of its elevation and placement the Racetrack may be expected to possess increased wind velocities in general.

Second, vertical measurements of wind speeds on Panamint Playa cannot be

expected to approximate the boundary layer on the Racetrack by virtue of its distinctive surface characteristics. Panamint Playa's surface is pock-marked by depressions (see Figure 4.19 on page 105) and dissected by lines of bushes. Unlike the uniform, flat surface of the Racetrack, Panamint has many obstacles that would be responsible for decreased wind speeds near the valley floor.

The influence of topography on windflow cannot be underestimated. As discussed in Chapter 6, the deflection of air through two corridors, directing fluid motion onto a very flat, clear terrain provides a rare combination of circumstances responsible for the Racetrack's unique surface processes. Air is topographically forced uphill and through restricted conduits; each condition in itself would result in increased wind speeds. Taken together, velocities are amplified even more so. The air currents then converge onto a planar surface, decreasing the height of the atmospheric boundary layer, focusing intense forces very close to the surface in the vicinity of many loose rocks, and causing them to slide.

7.4 The Role of Ice

The controversy surrounding the Racetrack's unusual surface features has centered upon the necessity of ice as an antecedent for sliding rock activity. There is no doubt that the Racetrack Playa endures freezing conditions. Ice was encountered in the ditch and in shady spots under bushes near the springs in December, 1996; evidence for general freezing conditions are observable long after thawing has occurred, as recorded by ice crystal molds on the surface itself (see Figure 4.3, page 88). However, the role of ice as a requisite condition for rock motion is questionable.

Just as Clements (1952) witnessed fresh tracks on Bonnie Claire Playa after a night of rain and above-freezing temperatures, the current national park ranger who patrols the Racetrack, Dan Dellinges, visited the playa both the day before and day after a movement event took place. Assigned to the Grapevine Ranger Station in the northeastern part of Death Valley National Park, Mr. Dellinges has been visiting the Racetrack for many years. The weather station at Scotty's Castle (only 5 kilometers from Grapevine, at nearly the same elevation as the Racetrack) keeps official weather records for the area. As concluded from data obtained in February and July 1996, temperatures at Scotty's Castle are roughly equivalent to those encountered at the Racetrack (see Table 4.1, page 84; Table 4.3, page 112). The day after a nighttime storm, new trails were noted even though freezing temperatures were not recorded at Scotty's Castle during that 24-hour period (Dan Dellinges, personal communication). However, this is only one person's view based on only one event. There are many other observations that question the necessity of ice.

Dating as far back as 1955, George Stanley hypothesized that rocks moved only when embedded in rigid ice sheets. He based his inference on the highly parallel nature of several trails spaced as far as 150 meters apart. Reid et al., (1995) found similar evidence for an ice sheet based on high degrees of congruence between distant tracks (see page 48), and they estimated its extent as 850 by 500 meters.

The climatic considerations for such an expanse of coherent ice are many. A rigid ice sheet capable of propelling rocks the size of those found on the Racetrack would have to be several centimeters thick. If the source of such an ice sheet is rain then the total amount of water on the playa would have to exceed the average annual total for Death Valley. This is not impossible given the Racetrack's increased altitude, yet it is unusual; 10

centimeters of water have been noted on the playa by Bradley in 1956 (Bradley, 1963), and 30 centimeters of snow were observed by D.W. Carney, a ranger assigned to the northern section of the national monument (Sharp and Carey, 1976). The combination of anomalously high accumulations of water *and* freezing conditions severe enough to solidify it decreases the odds considerably. Even taking into account the slight expansion of water (9%) upon freezing, the occurrence of ponds deep enough to form a cohesive ice sheet is nonetheless rare.

Sharp and Carey (1976) observed evidence of nearly annual sliding rock activity, with the greatest lapse between events only two years. Having monitored only thirty rocks over seven years, their reported frequency would no doubt have increased had the team been able to oversee the total population of rocks. Significant accumulation of ponding water on the playa has been a rare occurrence; far less common than the annual or bi-annual reports of sliding rocks.

If ice is *not* a requirement, then the slick clay-rich layer proposed by Sharp and Carey (described in section “7.2.1 Racetrack Sediments” on page 193) may form with no more than 1 or 2 centimeters of standing water. Clearly, this is a much more common condition.

Climatic data from other Mojave regions show that freezing conditions are possible. For example, Stanley (1955) reported National Weather Service record minimum temperatures of -13° C at Las Vegas, NV (altitude +620 meters); -15°C at Blythe, CA (altitude +82 meters); and -9°C at Furnace Creek, CA (altitude -55 meters). But these values are for nighttime lows, when winds are typically calm. Even in winter, desert temperatures may vary 20°C or more from night to day. A long-standing deep-freeze event,

persistent enough to cause solidification of an ice sheet several hundred meters in diameter seems implausible.

The motion of some sliding rocks points at inconsistencies with the ice sheet theory. Sharp and Carey (1976) noted evidence of tumbling among some of the stones they observed. Reid et al., (1996) explained that rocks may not necessarily be held rigidly frozen into the ice sheet, but may instead be loosely-fitting within “ice collars,” allowing for some tumbling and rotation within the context of general uniform ice motion. But Sharp and Carey (1976) also described and photographed a trail of a rock that was seemingly set into motion when another rock collided with it. While Reid et al., (1995) excused some trail anomalies by the “ice collar” hypothesis, they did not explain this billiard-ball-like action, nor did they present a reasonable explanation for the behavior of some rocks that fled the experimental corral (see Figure 2.9, page 46). In the 1996 mapping project, no discernible evidence of tumbling or “rock relays” were noted, yet there were several examples of trail thinning and widening, indicating rock rotation during traction events.

Many trails mapped by Stanley (1955) and Reid et al., (1995) show strikingly similar routes. High degrees of parallelism were noted by this survey, particularly at the extreme southern border of the playa (see Figure 4.13, page 97). This locality is unique in its sheltered setting, with one of two dolomite cliffs abutting it from the south. It is not unreasonable to surmise that this limited area is at least partially shaded during winter months, when the sun crosses the sky in its most southerly arc: Accumulating water might form an ice sheet here. Further evidence of ice forming at the southern cliff face may be suggested by rare scars left in talus gravels at the base of one of the cliffs (see Figure 4.12, page 96). The precondition of ice is a reasonable conclusion when considering just this

section of the playa; however, patterns observed in this survey lacked conclusive evidence to suggest its necessity. When the entire playa is studied it is clear that only *some* trails show parallelism; only a fraction of this subset shows congruence for entire trail lengths. The vast majority of trails, however, have similar net headings but few, if any, parallel segments. Even in winter, the more northerly sections of the boulder field receive adequate sunlight so that any ice formed at night would melt by day.

Some closely-spaced rocks show almost no parallelism whatsoever. If ice sheets were the driving mechanisms for all rock motion, then adjacent fragments should be more susceptible to uniform activity than those separated by hundreds of meters. Figure 7.5 shows two rocks with nearly identical physical trail characters implying that they began

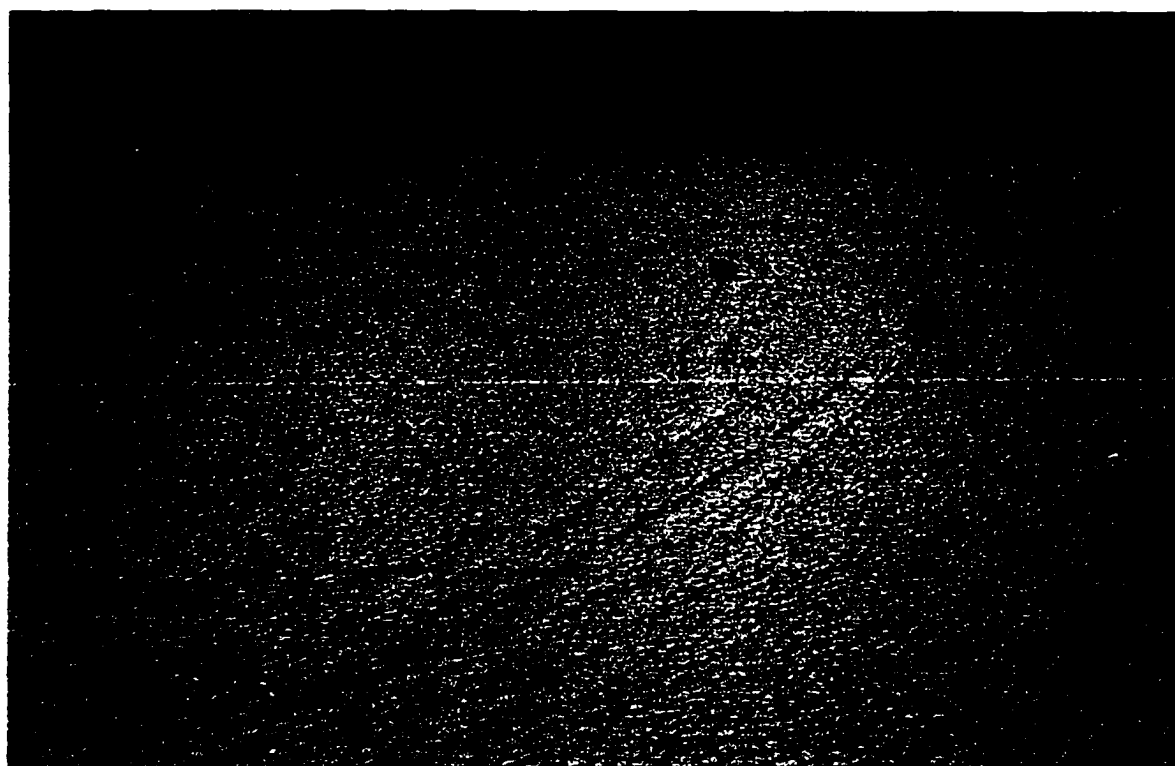


Figure 7.5: Two diverging rocks with similar trail signatures. Both rocks apparently began moving at “sitz marks” signifying a previous period of rest. Both trails have similar appearances and lengths, suggesting at concurrent activity. Since the trails diverge, they could not have been produced by a single ice sheet.

moving in the same episode; note, however, the lack of congruence between them. Note also the pronounced levees, and their irregular surface characteristics. If ice propelled rocks, levees would be smoother, altogether absent, or much wider than the rock footprint.

Trails showing parallelism near start points sometimes diverge farther down-route; this was noted by Stanley (1955, see Figure 2.4 on page 28) and Reid et al., (1995). Both surveys concluded that such divergence is the result of the fracture of one coherent ice sheet, propelling splinters carrying embedded rocks in different directions. This is a reasonable explanation for those selected features, however there are also instances of *convergence*, where parallelism occurs near trails' termini despite disparities in earlier motion and original placement. The most dramatic of these examples are shown in Figure 7.6, where several groups of rocks showing parallelism for limited lengths. Figures 7.7 and 7.8 show larger-scale maps of the end segments of five of these trails.

Uniformity among trails has lent credence to the ice floe theory, as concluded by Stanley (1955) and Reid et al., (1995); however, if it were the only motive process, then many more trails would should parallelism. Our survey shows that parallelism is the exception rather than a rule, and that a consideration of the total population of trails was necessary to show this. Two factors are operative in this matter: First, the use of differential GPS made the complete inventory visible for the first time; second, since trails are ephemeral, there is no doubt that the patterns traced in July 1996 were not identical to those mapped years (or decades) earlier. Any ultimate conclusions will have to evolve from follow-up studies in future years. Yet the indication from this survey is that ice, while not possible to eliminate as a contributor, is not a required component or precondition for sliding rock activity.

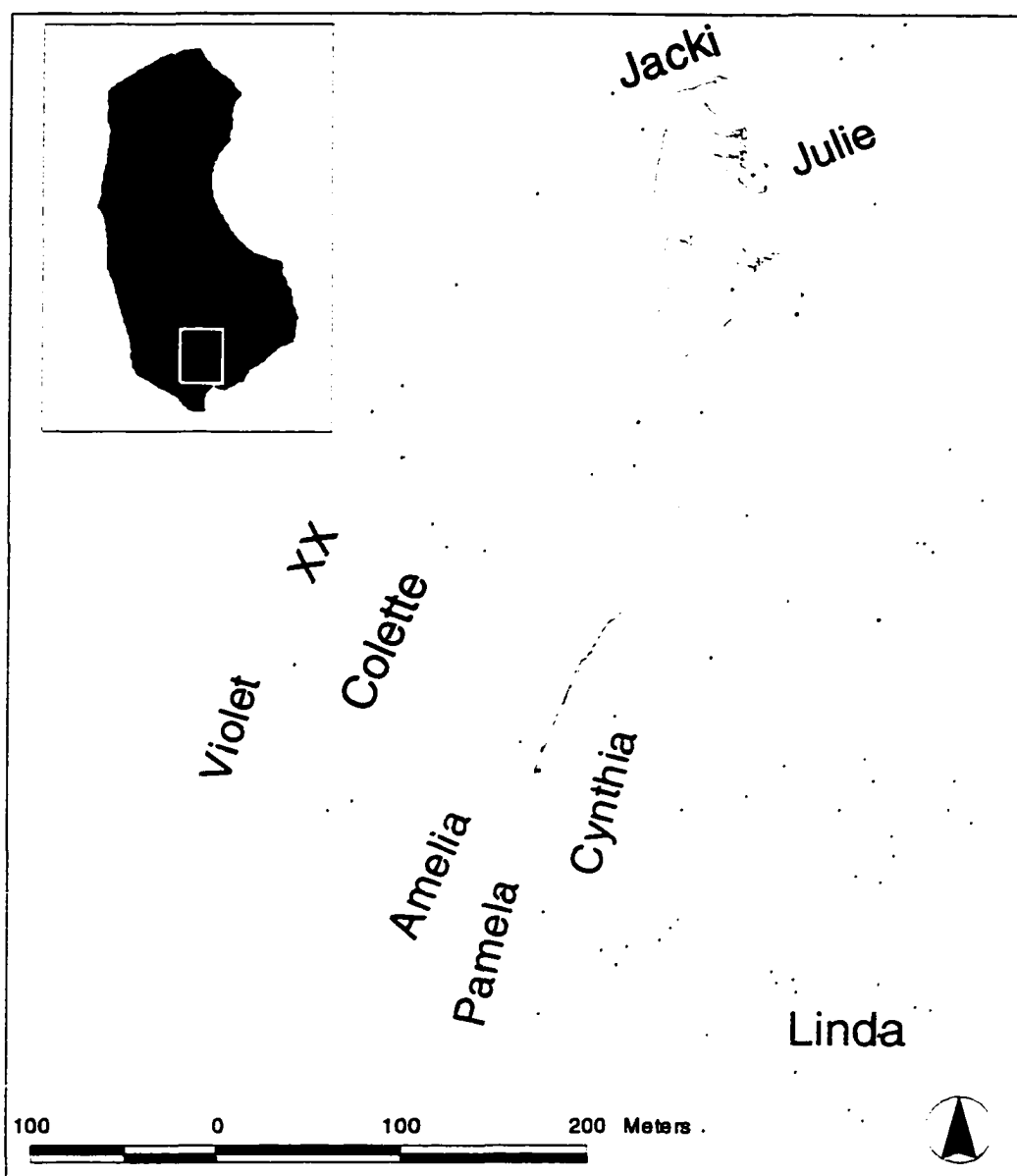


Figure 7.6: Several trails showing partial parallelism. Inset at top left shows the location of this larger scale map. Rock locations are indicated by point markers.

Violet, XX and Colette (left) are highly congruent. XX and Colette display remarkable symmetry and similar total trail length (222 and 257 meters, respectively). Yet Violet's trail, which crossed XX's near its origin, is only 123 meters in length. This disparity might ordinarily be explained by ice sheet break-up. However, since Violet's terminus lies between the tracks of Colette and XX (both of which traveled farther), how could this activity be explained by a fracturing ice sheet?

Linda's trail (lower right) was inscribed by only one rock, and yet it shows parallelism within its own contiguous path.

An unusual trio, Amelia, Pamela and Cynthia are highlighted in Figure 7.7. A zoom of the final motions of Jacki and Julie are shown in Figure 7.8.

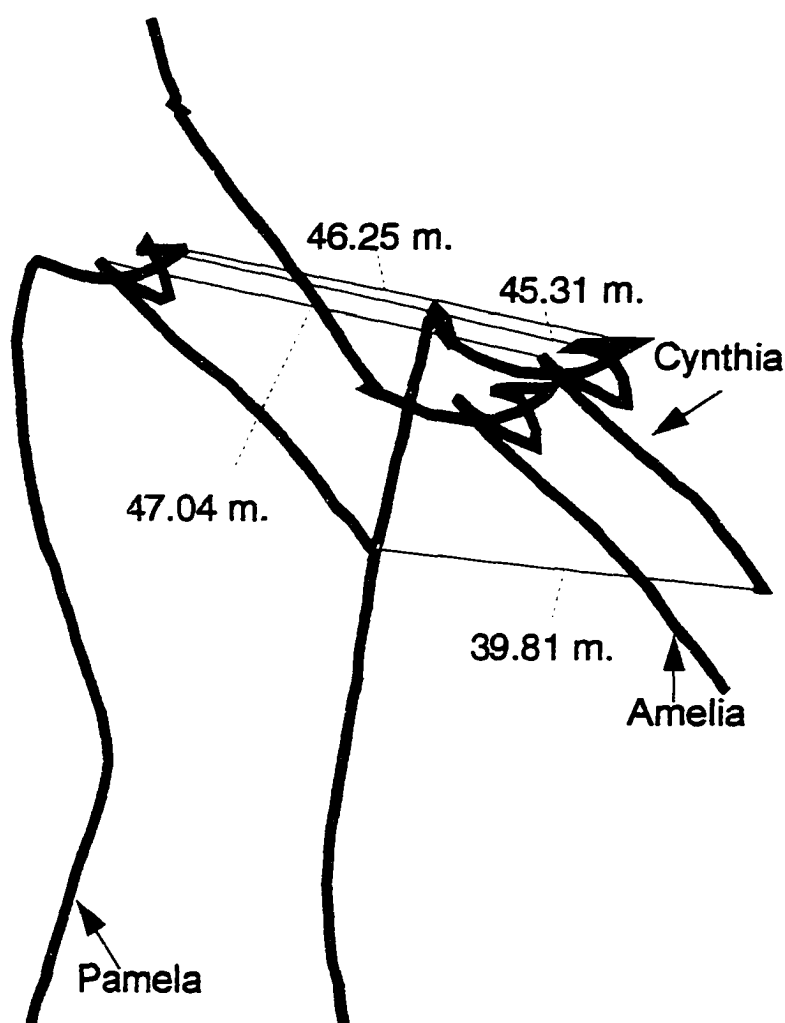


Figure 7.7: The congruent terminal segments of three trails, showing distances between analogous nodes. The ultimately-erratic behavior of the rocks Pamela, Amelia and Cynthia, was preceded by rather ordinary motion, as is shown in Figure 7.6. Note also the high degree of parallelism at the origins (Figure 7.6) and termini (above), interrupted by mid-trail divergence (Figure 7.6).

The ice sheet hypothesis may be employed to explain parallelism of total trail lengths or of trail origin segments, but it does not provide a logical model for trails whose parallelisms occur at termini. These three rocks moved in tandem at the outset and then independently for several tens of meters (Figure 7.6), but ultimately showed identical signatures near their end points. The nature of these trails shows that they represent a single episode of motion; there is no indication (i.e., sitz marks, changes in trail character) that the rocks moved in more than one event.

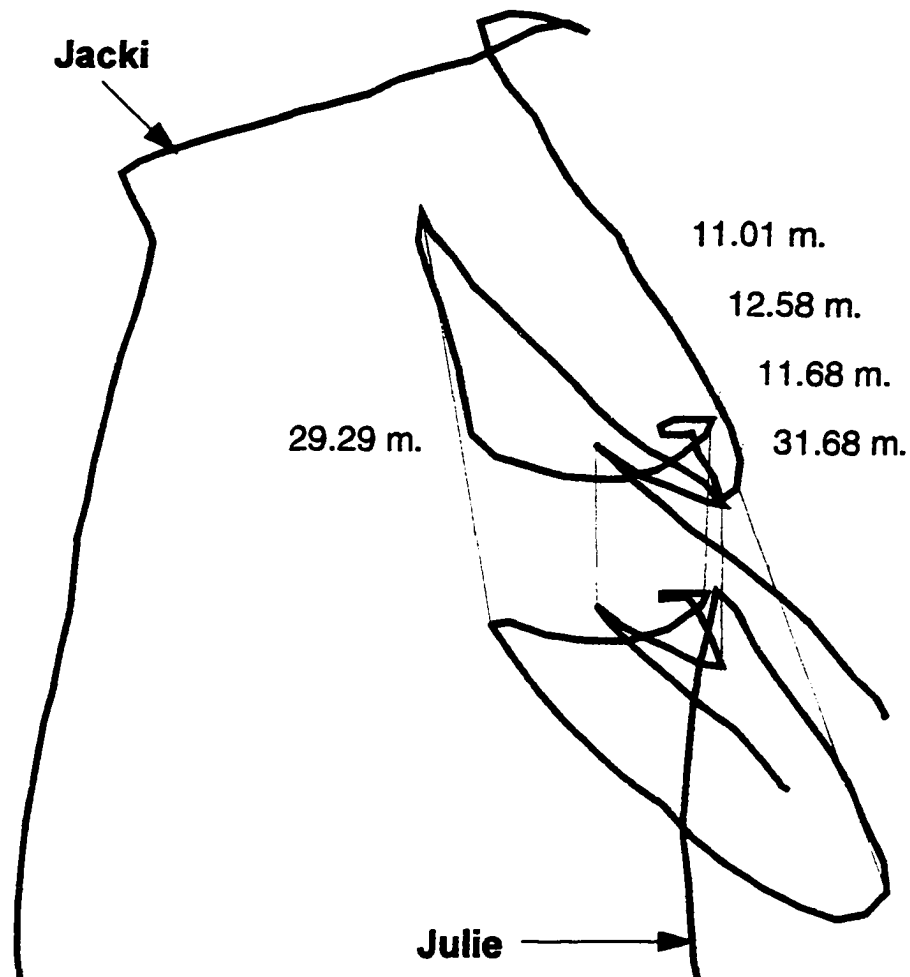


Figure 7.8: Large scale map of the trails of Jacki and Julie. Note the cursory similarities in trail patterns, but the highly variable distances between nodes. Such complementary motion, although quite congruent, cannot be explained by ice sheet entrainment. The rocks *continually converged* throughout their travels although every turn in each trail has an analog in the other. Even if these paths span several motion episodes, earlier segments would have been degraded by ice floes if in fact the final parallelisms were caused by them.

7.5 Seasonal Climatic Considerations

Long-term monitoring visits conducted in the past by Stanley (1955), Sharp and Carey (1976) and Reid et al. (1995) took place during the more-hospitable spring seasons, and it was assumed that activity took place mostly during winter storms. While this assumption cannot be definitively refuted by this project, the possibility of summer activity cannot be discounted. Since water is a required component, whether solid or liquid, past researchers inferred that activity on the playa coincided with Death Valley's "wet" season. Yet there is evidence to suggest that conditions suitable for sliding rock activity exist at other times of the year.

Summer storms in the form of Southwest monsoons are highly localized events, frequently associated with orographic uplift and convective warming of air over topographic highs (i.e., mountains). Flash floods, for example, are most common in summer months in this region when cloudbursts may produce significant rainfall over a limited geographic range; these events can cause sudden flooding in areas dozens of kilometers away where skies may be clear. Hence, since no meteorological data are logged in and around the Racetrack Basin, and since it is a hydrologically-closed basin, summer cloud bursts in the surrounding Last Chance Range may go unnoticed.

Storms of this type caused the Racetrack Road to close due to wash-outs and high standing water about a week before this project's mapping mission. As pictured in Figures 4.21 (page 115) and 4.22 (page 116) evidence of these storms was observed. It is likely that conditions favoring rock movement may have existed not too long before the July 1996 visit, especially if associated winds persisted after surface slickness increased. Furthermore, if cyanobacteria in the uppermost surface of clays contribute to the playa's slick-

ness, it follows that these biogenic effects would be maximized during the warmer months.

To contrast, a brief visit to the playa in late March 1997 yielded some interesting observations. Although no follow-up mapping took place, a Trimble Pro-XL was used to determine whether selected rocks had moved during the winter of 1996-1997. Examination of the trails, spot fixes of the rocks, and comparison to data gleaned in July 1996 showed no apparent evidence of activity. There was, however, one trail that appeared fresh by comparison to the others. It was rather deeply recessed, and it was well-lined with small mud curls ("Special K"). The presence of this fine clay indicated that the trail might have been produced sometime *after* the surveying mission, since these mud curls are easily deflated. Using the GPS receiver and the July 1996 map it was clear that this was the trail of "Ellen," rock 91. The trail existed in the same location as it was previously mapped; but its character had changed.

In July 1996, Ellen's trail had a smooth surface, but eight months later its trace was scarred by ~1 centimeter mud curls. The existence of the mud curls indicates that water had collected in the trail (a local low) and had not yet been deflated. Field notes confirmed that this trail was relatively deep, which explains why other trails may either not have collected water, or had resulting mud curls blown away by the time of the March visit. In either case the alteration of Ellen's trail shows that water had accumulated on the playa at some point during the winter of 1996-1997, enough, in fact, for the smallest clay fraction to form the necessary "film," yet no rocks moved from their previously recorded locations. It is possible that winds at the Racetrack during the winter of 1996-1997 were not powerful enough to set any of the rocks in motion.

The origin of Ellen's trail lies near the eastern edge of the sliding rock field, south

and slightly downslope of the springs. The contribution of these features cannot be discounted; they are possibly a significant perennial water source. The presence of mud curls in this eastern trail may indicate increased spring production during the period just prior to the March 1997 visit, and may explain why no trails in the west displayed the same degree of alteration.

Since trails show a general trend increasing in length eastward it seems plausible that production of spring water, sometimes substantial enough to cause localized flooding, plays a contributory role in the essential slickening of the surface muds.

7.6 Topography

The topography of local basins plays a significant role in the nature of aeolian processes that shape them. For example, the parallel-striking depressions of Owens, Saline, Eureka, Panamint and Death valleys each contain localized accumulations of sand. It is expected that sand grains are deposited in places where local wind velocities decrease significantly, thus inhibiting their suspension by air. Such deposits are usually upwind of a barrier. Despite their proximity, adjacency and expected prevailing wind similarities, dune placement in these valleys is nonuniform. Dune fields are found in the southwest section of Owens Valley, to the west in Saline Valley, in the south at Eureka Dunes, at the northernmost extent of Panamint Basin, and in the sheltered western portion of Death Valley (Norris and Webb, 1990). In each case the dunes are deposited as moving air approaches an obstacle, usually a steep mountain face. Hence, inferred wind patterns must be highly localized and dependent on topography.

The unique terrain skeleton of the Racetrack Basin in context of prevailing winds

has been noted in the literature, and confirmed by this project’s analyses. Bacon, Cahill and Tombrello (1996) cited the 2-kilometer vertical relief near Death Valley as a cause of the high wind speeds possible in the region. Sharp and Carey (1976) referred to the Race-track’s topographic configurations as enhancements for localized wind channeling and increased velocity. Similar observations were made by Shelton (1953).

Among the most significant correlations found in this research is the apparent influence of surrounding topography on the motion of sliding rocks. Figure 7.9 shows a histogram of the entire 2000-meter buffer zone’s pixel orientations (the aspect map from which this data set was gleaned appears in Figure 7.10). The unequal distribution reflects

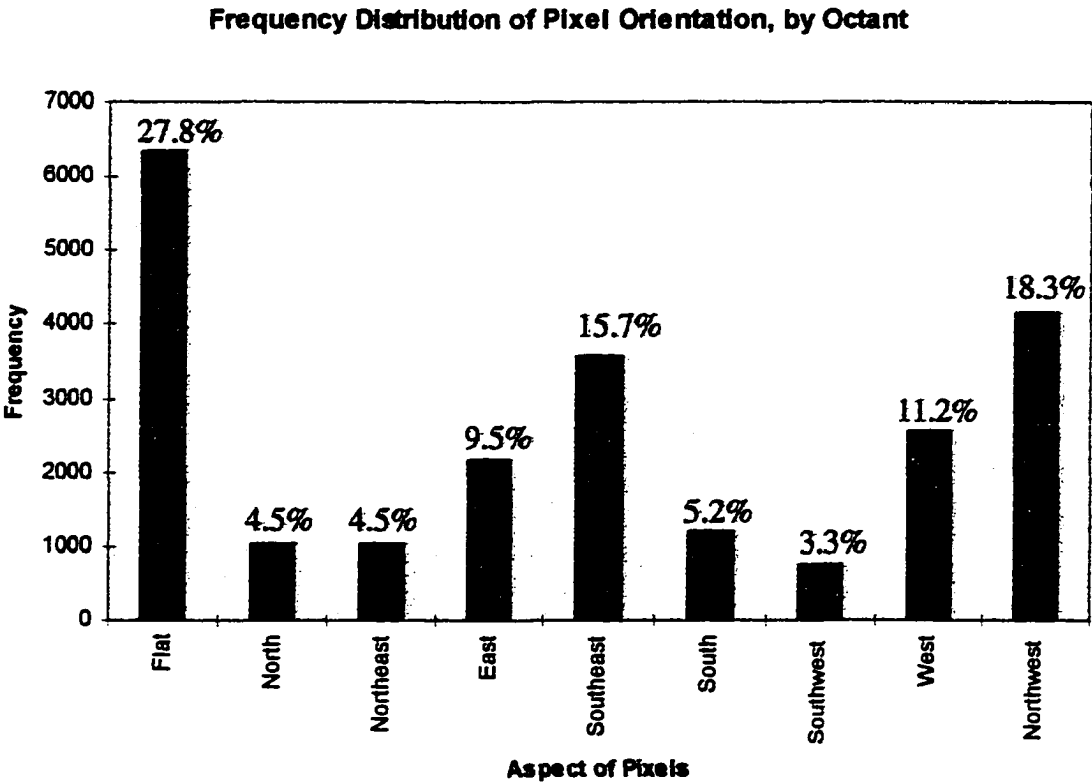


Figure 7.9: Frequency distribution of pixel aspects, by number and percentage, of the 2000-meter buffer zone. Note the significance of the east, southeast, west and northwest octants, apparently influencing the direction of sliding rock motion. When compared to Figure 5.28 (page 152), these peaks are offset 90 degrees from the significant trail headings.

the general north-south strike of the valley, showing significant spikes in the east-southeast and west-northwest. While some of these facets lie north of the boulder field (on the lee side, considering the majority of trail headings) considerable contributors lie in the two chutes at the playa's south end. Since prevailing winds emanate from the south or southwest, air is probably forced through these saddles (see Figure 6.7, page 177) and directed onto the playa. The surrounding topography shows significant proportions of slope orientations orthogonal to mean trail headings (see Figure 5.27 on page 152 and Figure 5.28 on page 152), thus suggesting influence over sliding rock motion. When visibility profiles of selected rock start points are considered, analyses show a statistically significant relationship between trail headings and viewshed configuration (see "6.3.2 Viewshed Analyses" on page 180 and "6.3.3 Trail Heading Correlations to Surrounding Visible Topography" on page 188).

Even earlier events preceding those that produced the patterns recorded in July

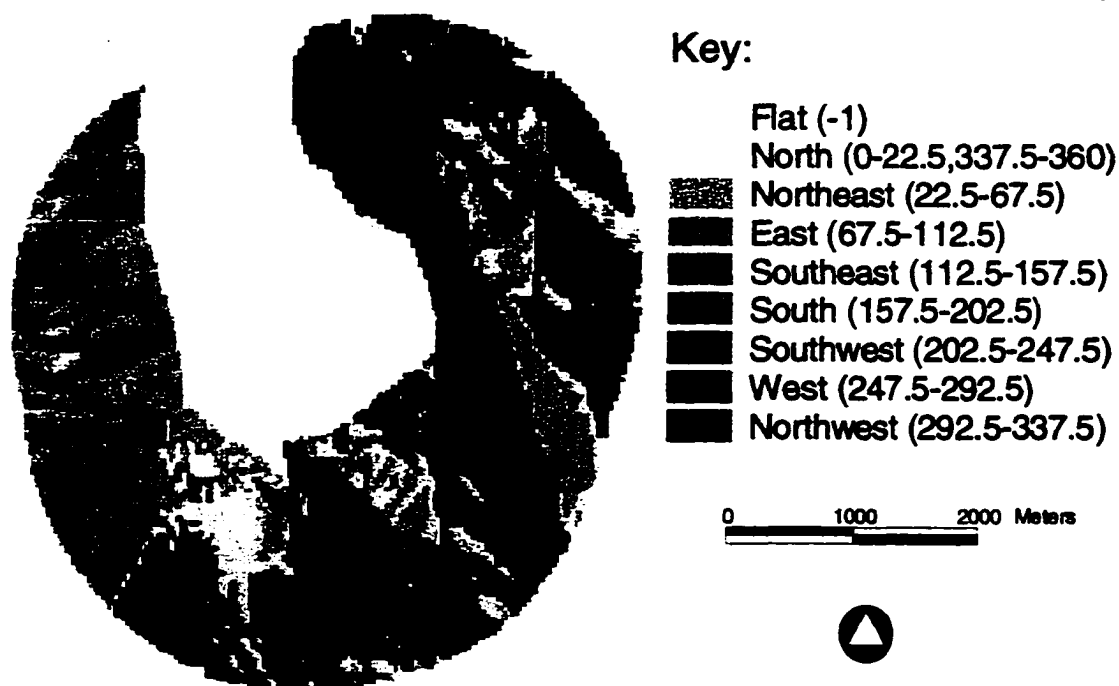


Figure 7.10: Aspect map of 2000-meter buffer zone. The total number of pixels in each class were tallied as displayed in Figure 7.9 (page 214).

1996 may be inferred to be affected by topography. When considering the bounding polygon of trail start points (Figure 6.8, page 178) within the context of surrounding slopes it appears that rocks arrived at their “origins” by prior motive forces that channeled through those same southern end chutes. Figure 7.11 shows an overlay of the origin-point polygon on a derived contour map. Note the congruence of the initial positions of rocks with the terrain that surrounds them. Since rocks are assumed to have arrived at their current-trail start points by natural causes, and 92% of the rocks found on the playa are presumed to be from the southern dolomite cliffs (see Figure 5.4, page 132), the observed patterns are consistent with the idea that wind tunneling has been a determining factor for rock motion in prior (unmapped) events as well as the most recent (mapped) episodes.

Visual images of these two main topographic corridors as viewed from the playa surface are shown in Figures 7.12 and 7.13.

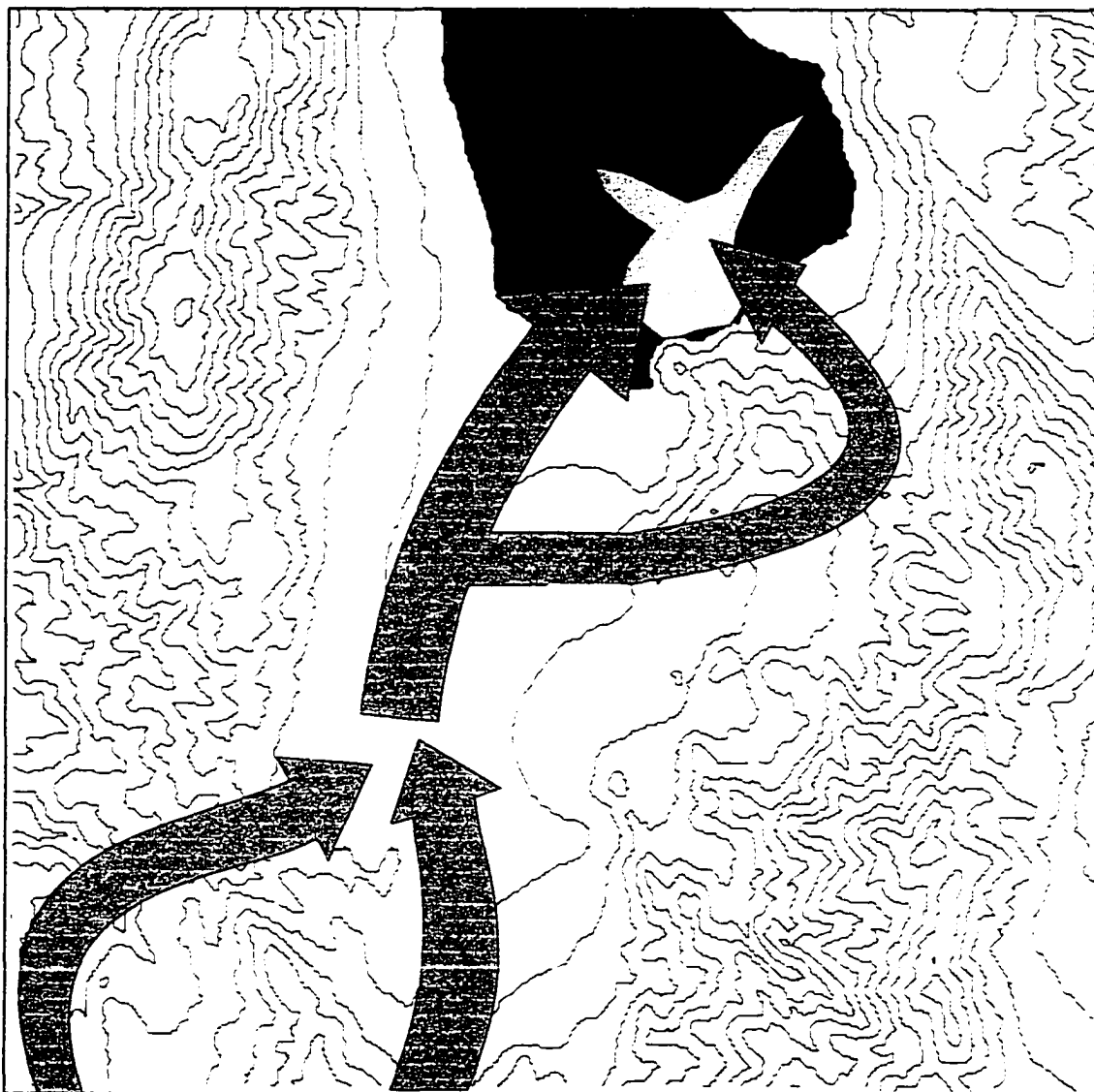


Figure 7.11: Contour map of Racetrack Basin's south end, including the sliding rock start point bounding polygon. Note how inferred air patterns correspond to the spatial distribution of trail origins. Rocks were first moved into these localities by channeling winds before the most recent (mapped) event occurred. Contour interval, 50 meters.

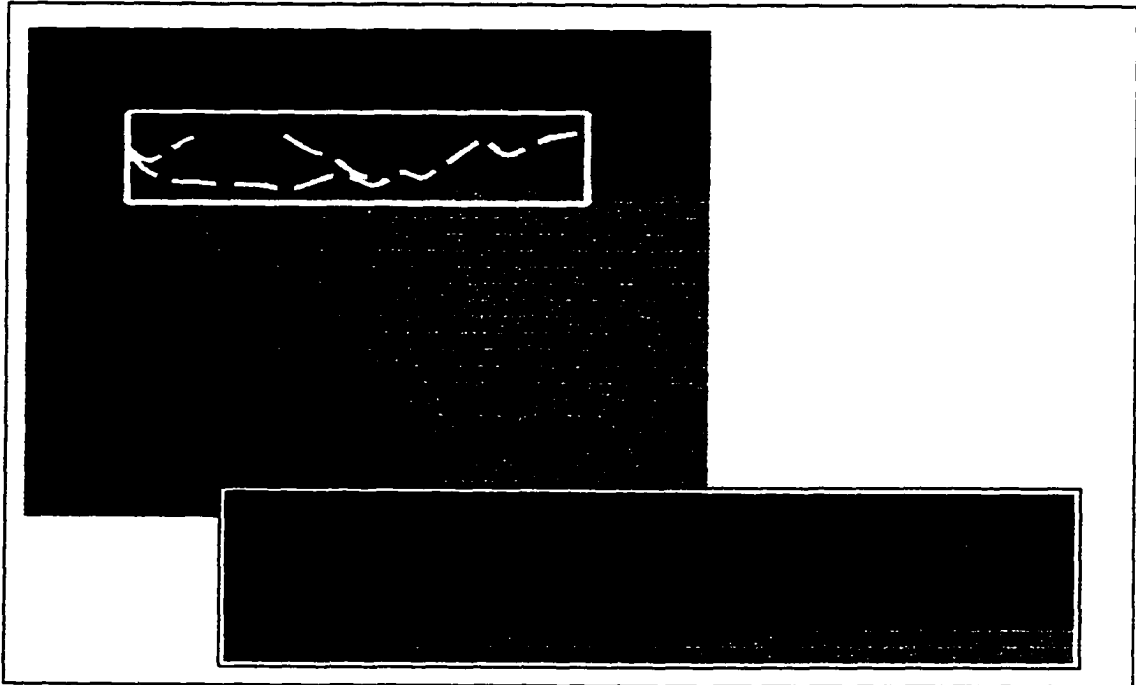


Figure 7.12: The southwest topographic corridor, as viewed from the Racetrack Playa surface.

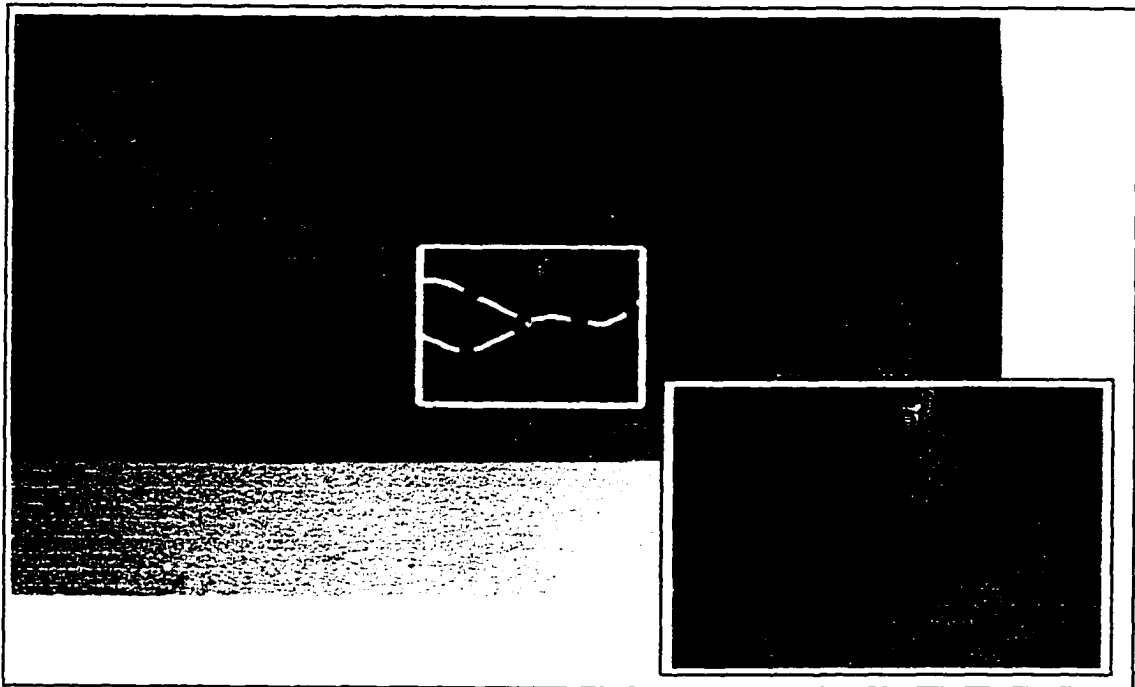


Figure 7.13: The southeast topographic corridor, as viewed from the Racetrack Playa surface.

7.7 Inferred Aerodynamics of the Racetrack Basin

Little evidence was gained in this survey in support of ice floe activity. If ice were a factor, its effect is limited to the southernmost extent of the playa (most notably, Figure 4.12 [page 96] shows a rock trail through a gravel deposit). It is the conclusion of this study that wind acting alone can account for most sliding rock episodes. The direction of these winds is clearly indicated by the trails themselves, and is further supported by terrain analysis of the southern end of the basin. However, the nature of these winds is complex.

7.7.1 Wind Shear as a Transport Mechanism

Given the average size of a typical sliding rock (in the cobble range, see “5.3.2 Classification by Rock Size” on page 133) it is well established that the rocks move by traction. The trails themselves provide the most convincing evidence for this mechanism. Yet it has been noted (Sharp and Carey, 1976) that some trails display distinctive gouges, indicating occasional tumbling.

The smallest particles (i.e., sand, silt, dust) are easily transported in suspension by moving air. The competence of air as a transporting medium is dependent on wind speed, gravity, and the density of the air, which is a function of its chemical composition, pressure and temperature. Figure 7.14 shows the relative horizontal wind speeds necessary to initiate movement of small particles. It is generally agreed that particles up to sand-sized grains are readily transported in suspension by wind, yet pebbles of various grades may be carried as well; larger particles can be moved by saltation or traction. Extrapolating from the data plotted in Figure 7.14 it is not inconceivable to explain slightly larger particles being moved by more forceful air currents, yet the movement of boulders as subaerial bed-

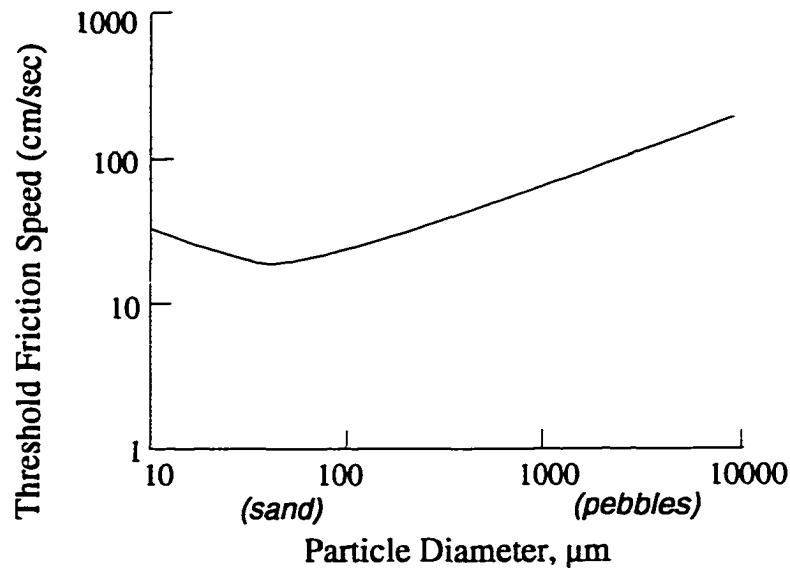


Figure 7.14: Wind speeds necessary to initiate movement of small particles on Earth. (After Greeley and Iversen, 1985.)

load is difficult to rectify within the parameters of this threshold-particle size relationship. This graph holds true for straight winds, but rotational air currents need to be considered as a significant component of rock activity. A discussion of the influence of whirlwinds follows in “7.7.2 The Role of Dust Devils” on page 221.

Strong shearing winds can induce movement of Racetrack rocks by saltation or traction if the surface is sufficiently friction-free. Such conditions may exist a day or two after surface flooding during winter or summer monsoon-related storm activity. As noted by Bacon, Cahill and Tombrello (1996, see page 51), measurements of wind speeds on Owens Lake suggest that wind alone can indeed provide enough force to overcome rocks’ coefficients of static friction.

Some rocks show evidence of bulldozing activity, resulting in the formation of muddy bow-waves; a few cobbles were seen “frozen” in these self-induced mounds. It is conceivable that this configuration supports future activity in that rocks are not typically recessed into the playa muds, but rather rest slightly higher than the playa surface. In such

a position they are more likely to extend above the playa boundary layer, and receive the full force of the wind.

A review of collected wind data (see “4.5.1 Meteorological Survey, December 1996” on page 120) suggests that, like most fluid flow through a channel, velocities are greatest farthest from interfaces, in this case near the center of the playa. This may explain why westernmost rocks nearest the road left anomalously short trails. Wind speeds were found to be greatest near the playa’s center, consistent with the distribution of largest rocks in that vicinity (see Figure 5.6 on page 135). Although trail lengths generally increased towards the eastern edge of the boulder field, these rocks are generally less massive and subject to more frequent low-friction surface conditions (see “7.5 Seasonal Climatic Considerations” on page 211).

7.7.2 The Role of Dust Devils

The absence of statistically significant relationships between rock shape or size, and trail length or straightness is problematic and difficult to explain in terms of forces generated by horizontal winds. Consequently, motive forces other than horizontal wind shear need to be considered.

An unmentioned potential driving mechanism for the sliding rocks involves the action of dust devils. These whirlwinds are common in desert areas, particularly during summer months. No previous researchers have seriously considered their role in moving the Racetrack’s inventory of surface rocks, probably because most of their field work had been conducted during cooler seasons when such phenomena are not frequent. Since the GPS mapping project was undertaken in July, dust devils *were* witnessed; their sudden appearance and inferred intensity convinced this author that they may provide forces sub-

stantial enough to set rocks in motion when surface conditions support movement.

Because the playa is usually not visited during July and August, and because most scientific field work takes place during more hospitable months it is easy to understand why dust devils have not been mentioned in the literature as a cause of sliding rock activity.

Dust devils, common and significant meteorologic phenomena, are isolated wind vortices that form most commonly during midday hours in desert regions during summer months. They are most common on sunny days with relatively calm winds; too much air movement causes the air to mix, which inhibits the formation of necessary convection currents. Local surface "hot spots" absorb solar energy, resulting in extremely high ground temperatures and extremely steep temperature gradients at low atmospheric levels. Vertical motion can occur freely in the heated layer and the slightest disturbance in the air will cause it to overturn (Woodcock, 1991). As a parcel of heated air accelerates upwards horizontal wind shear sets the rising column spinning (Figure 7.15). Temperatures inside a

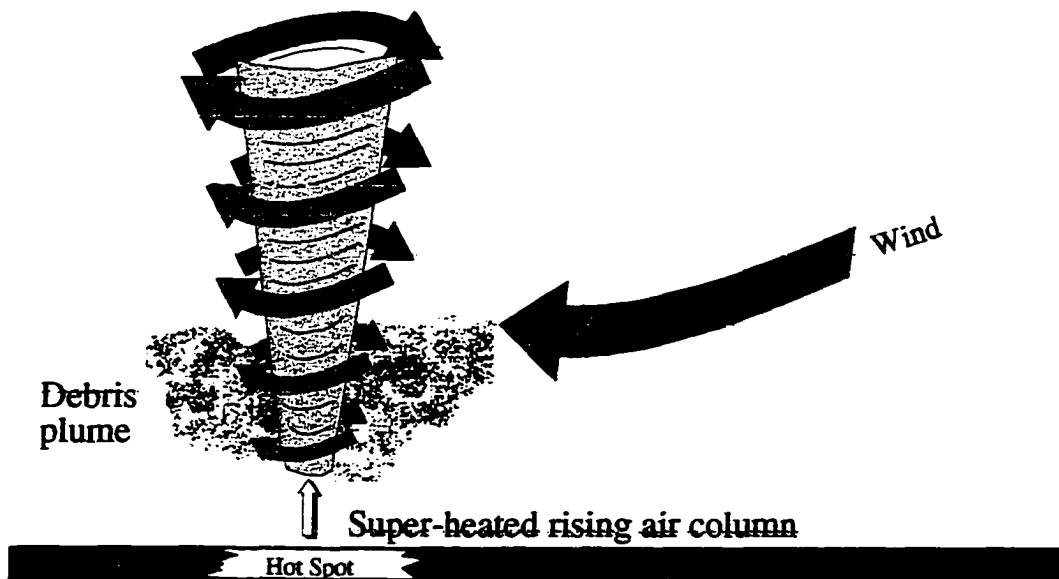


Figure 7.15: Simplified diagram of dust devil morphology. A super-adiabatic lapse rate results from intense ground temperatures warming air at the interface. Decreased pressures send this column of air rising rapidly. Spinning results from horizontal winds, which can cause either clockwise or counterclockwise rotation. (After Williams, 1992).

dust devil vortex are typically about 5°C warmer than those of surrounding air (Greeley and Iversen, 1985). It should be noted that, unlike tornadoes in northern latitudes, dust devils may rotate clockwise or counterclockwise (Sinclair, 1969) depending on the torque of the controlling airflow. Like tornadoes, they are steered by prevailing winds.

Since air within the spinning column is hot and moving rapidly its pressure is greatly decreased. Greeley and Iversen (1985), reported that maximum pressure deviations from the outside to the inner vortex is typically about -4 millibars, allowing surrounding air to flow towards it from all directions. Dust devils last as long as their supply of warm air is available, or until physical obstacles impede their motion (Woodcock, 1991). When directed over an area of loose soil as is common in the desert southwest, the extent of this dynamic thermal is visually defined by a rising plume of debris. Figure 7.16 shows a typical circulating dust plume caused by a desert whirlwind.



Figure 7.16: A typical desert dust devil (in Arizona) showing rising plume of debris (Ludlum, 1991).

Snow and McClelland (1990) observed dust devils over a 260 km² area of White Sands Missile Range in New Mexico for a total of seventy-one days in 1986 and 1987. Of 1265 dust devils observed they found that the majority (56.6%) lasted under one minute. Rarely do dust devils persist for more than 5 minutes; Snow and McClelland's (1990) inventory showed that only 2% of these convective features have such extensive lifetimes. Data from the Tucson Basin show that dust devils can endure for as long as 19 minutes (Sinclair, 1969).

Studies conducted in the Avra Valley and Tucson Basin conclude that maximum dust devil activity occurs between 1:00 and 2:00 PM (local time) which corresponds to maximum ground temperatures and convective heat flux (Sinclair, 1969). White Sands dust devils show similar diurnal variation, occurring most often between 12:30 and 1:00 PM (local time) (Snow and McClelland, 1990). The offset temporal distribution may be due to the more easterly position of this observation area, in New Mexico as opposed to Arizona. (Note also that while Arizona and New Mexico both lie in the Mountain Time Zone, Arizona does not switch to Savings Time during summer months; hence Arizona's maximum surface heating actually lags behind New Mexico's by an hour or more.) Sinclair (1969) cites Williams (1948) as having observed similar patterns in the Mojave Desert.

Mature dust devil morphology consists of three vertical regions, as described by Ludlum (1991). The lowest level is a shallow, frictional level near the ground where air and dust spiral into the core of the whirl. The second region is a stable vortex where pressure and centrifugal forces are in balance. The highest segment consists of unstable, turbulent air which typically diffuses radially with increasing height.

Dust devils are categorized by size, unlike tornadoes and hurricanes which are classified by wind speeds. They are described as “small” (under 1 meter in diameter), “moderate” (up to 10 meters), “large” (up to 100 meters) and “gigantic” or “extra large” (over 100 meters) (Woodcock, 1991). Most dust devils observed are moderate in size (56% of the total in the Arizona inventory [Sinclair, 1969], 46% of those observed in New Mexico [Snow and McClelland, 1990]). Size class and temporal duration are inversely related (Woodcock, 1991). Those having diameters less than 3 meters last only about 0.5 minutes, while those having diameters of 3-15, 15-30 and greater than 30 meters, average 1.5, 3.5 and 6 minute duration, respectively (Greeley and Iversen, 1985). Heights of dust devils vary from under 100 meters to over 5,000 meters above the surface (Woodcock, 1991). Wind velocities are generally estimated to be on the order of 10 meters per second for tangential, and 8 meters per second for vertical airflow (Greeley and Iversen, 1985).

However, the relatively unimpressive wind speeds approximated for dust devils are in conflict with several observations noted of their intensity. Tom Gill of the U.S. Department of Agriculture’s Wind Erosion and Water Conservation Research Division made several observations of dust devils near the southern New Mexico-Texas border in 1996. A flat caliche-surfaced rodeo arena spawned periodic vortices, one after another, which spun out of the arena and headed generally west-to-east along a paved road and onto a grass-land. They were uniformly medium-sized, and they followed a highly predictable path. At one point the observer saw a pickup truck drive along the road and through one of the columns; the air either pushed or *physically lifted* the truck and repositioned it in the next traffic lane (Tom Gill, personal communication, 1997).

Another type of whirlwind, typically found in urban environments, are eddies that

form as a result of converging conduits of forced wind at the meeting of two intersecting streets. Investigations of these interfaces have been conducted for use in pollution dispersion studies. It is clear that vortex formation is not uncommon in urban canyons (DePaul and Shieh, 1986; Dabberdt and Hoydysh, 1991). Analogous fluid flow through colliding air conduits are found in natural settings as strong winds blowing around mountain ridges. Ludlum (1991) states that the whirls caused by converging air channels around mountains have been known to lift roofs and overturn parked airplanes.

Unlike boundary-layer airflow, dust devils set objects into motion by a combination of horizontal forces and vertical lifting. The severe pressure drop by a passing vortex may be enough to relieve some of the weight of even massive objects, making them more vulnerable to the rotational or steering winds. Unlike straight winds which preferentially sort fine sediments by size (see Figure 7.18, page 220), wind tunnel studies conducted at Iowa State University and reported by Greeley and Iversen (1985) showed that vortices entrain a broad spectrum of particles simultaneously, without regard for size, density or shape. While results from scaled-down dust devil modeling may not be applicable in all natural conditions, the conclusion that threshold speeds are nearly independent of particle diameter (Greeley and Iversen, 1985) is quite significant, and contrary to the behavior of particles in boundary-layer winds.

It was shown earlier (see “5.4 Regression Analyses” on page 153) that trail lengths in this survey are *not* a function of rock size, shape or density (lithology). The high wind speeds and low pressures of dust devils could produce such results.

The sliding rocks appear to record vortex activity, especially in the convoluted scribbles found at the ends of several trails; Figure 7.6 (page 208) shows five such trails

(Jacki, Julie, Amelia, Pamela, Cynthia). Figure 7.17 shows the route of rock #160, “Helen,” which shows some relatively straight motion, followed by a “double knot” of counterclockwise and then clockwise patterns. While extremely difficult to describe at first, this “ornamentation” is consistent with the cyclonic and anti-cyclonic circulation possible in dust devils. While rocks are clearly pushed along the surface to produce the trails (see “7.7.1 Wind Shear as a Transport Mechanism” on page 219), a sudden drop of pressure within a vortex may substantially decrease their effective weights, thus lowering their coefficients of static friction to within the necessary threshold. Once set into motion, the rock may be propelled by wind speeds roughly *half* of those necessary to initiate activity (Bacon, Cahill and Tombrello, 1996). Hence, even momentary contact with a traveling dust devil may be enough to start rock sliding action, freeing it to continue with the aid of

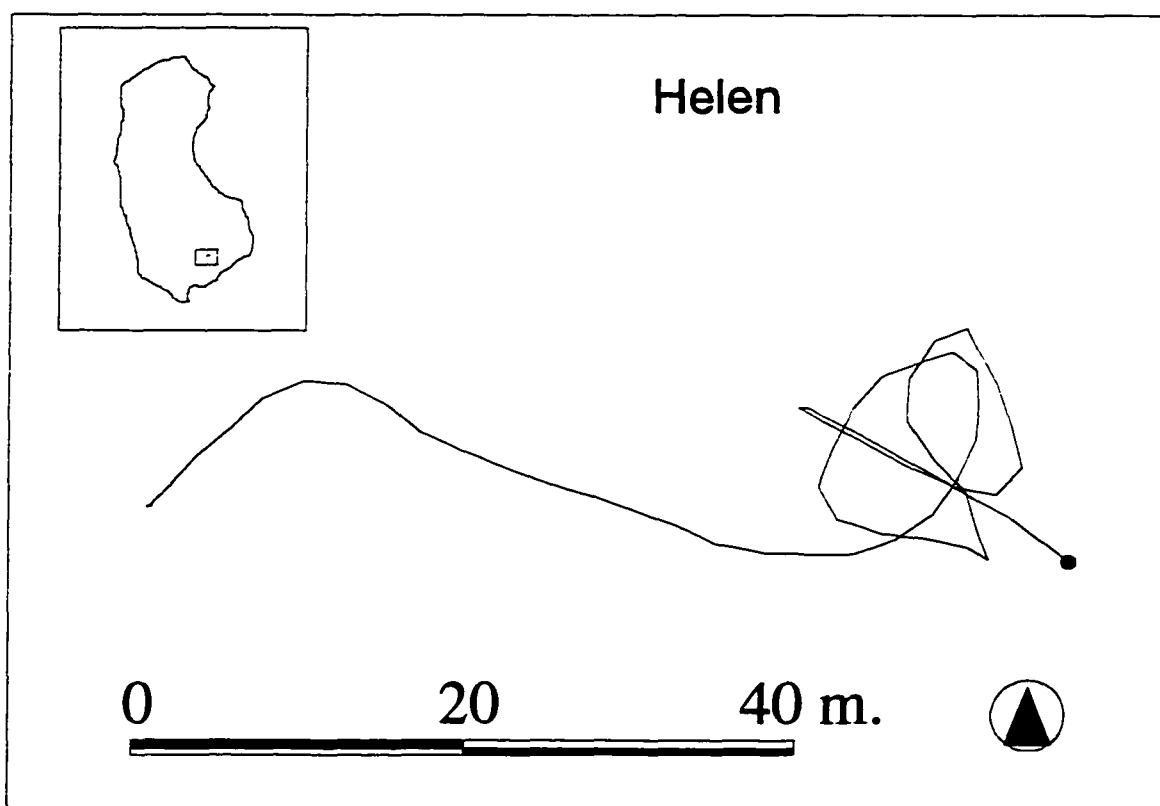


Figure 7.17: The trail produced by rock 160, “Helen.” The inset (upper left) shows the relative position of this trail in context of the playa perimeter.

horizontal steering winds that provide forces greater than the dynamic friction threshold. Thus relatively straight trails can be explained. Traces such as those produced by Amelia, Cynthia, Pamela (Figure 7.7, page 214); Jacki, Julie (Figure 7.8, page 210); and Helen (Figure 7.17, page 227) may indicate initial propulsion and relatively-straight movement caused by wind shear followed by ultimate entanglement within a whirlwind. The distances separating these rocks implies that the vortices that may have caused this motion fall within the range of “large” or “extra large” categories (both of which tend to persist for several minutes). Changes in direction as displayed by Helen may be explained by contact with a single wandering dust devil, or with more than one (in this case with opposite spins).

An examination of the distribution of crooked, circuitous trails shows that they are more numerous in the north-central boulder field (Figure 7.18 below, and Figure 5.25 on page 149). Trails closer to the playa’s margins tend to be straighter. This is consistent with the occurrence of whirlwinds at mountain ridge junctions.

Propelled mud deposits that form as finger-like projections of standing, turbid water (see “2.9 Bradley, 1963” on page 40 and “4.2.4 Surface Scars and Clay Mounds” on page 91) also show evidence of rotation. Figure 7.19 shows two such extensions, positioned on the playa in a counterclockwise swirl. It is likely that these mud-curl scars formed by whirlwind activity.

7.7.3 Topographic Control of Observed Dust Devil Origin Localities

As noted by Dr. Gill (see page 225), dust devils appear to originate in non-random geographic locations. Confirming his observations are the long-term dust devil inventories conducted by Sinclair (1969) and Snow and McClelland (1990). Dust devils sighted

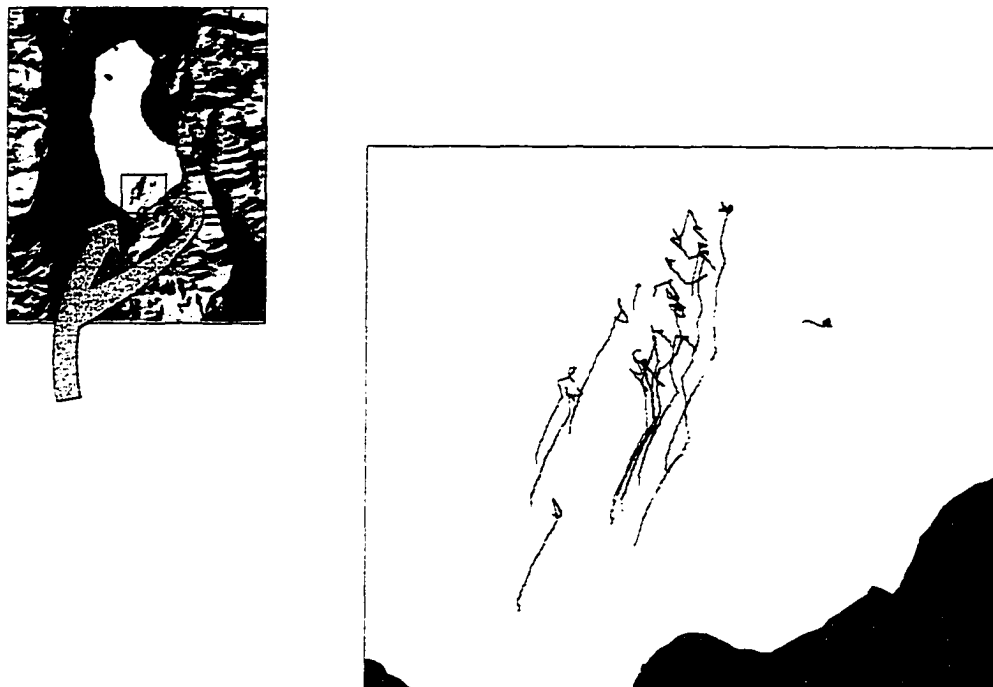


Figure 7.18: Convoluted trails are more common near the middle of the playa. This is likely due to the formation of whirlwinds as near-orthogonal channels of air collide at this locality.

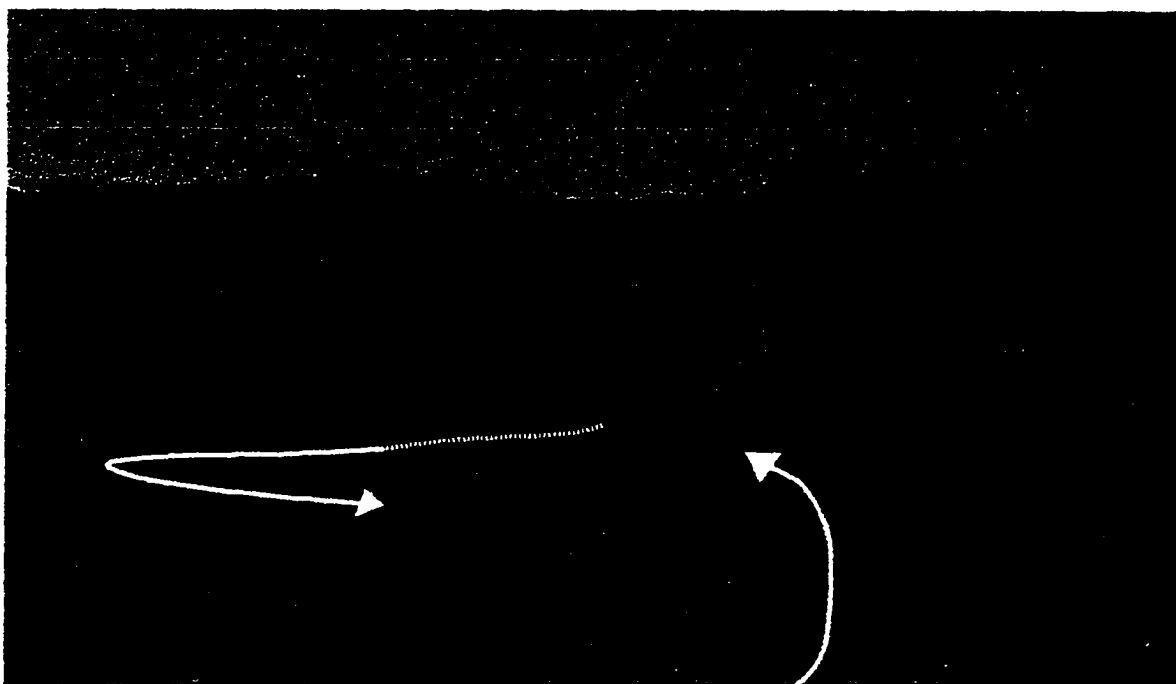


Figure 7.19: Curved mud deposits suggest counterclockwise rotation. Arrows were added to delineate the extents of two mud projections in the central part of the playa as observed in December 1996. Note the southwest topographic corridor in the distance.

in the Tucson Basin and Avra Valley, AZ, show distinctive spatial distributions. Sinclair (1969) attributed this unequal arrangement to three possible explanations: 1) the availability of dust allowed for better observation in certain localities; 2) the existence of surface hot spots; and 3) the influence of ground-level winds over terrain peculiarities.

The first hypothesis implies that dust devil distribution may in fact be random, but detection is enhanced in areas of fine grained, unconsolidated surface cover. This idea contradicts the census data of Sinclair (1969) and Snow and McClelland (1990) who observed areas of similar surface characteristics with little or no dust devil activity.

Local hot spots appear to exist in areas where dust devils are periodically spawned, as suggested by Tom Gill (1997, personal communication). Why the ground and hence the adjacent air should be warmer (in spots) than seemingly identical ground in other parts of observing areas is not readily apparent (Sinclair, 1969). Snow and McClelland (1990) noted similar superficial uniformity of albedo, thermal conductivity and surface wetness of adjoining areas with highly disproportionate dust devil activity. Both long-term inventories showed that whirlwinds tend to form over relatively flat surfaces, like parking lots or roads, much like the rodeo arena observed by Tom Gill. The propensity for dust devils to form over flat, horizontal or slightly inclined terrain is likely due to the increased solar absorption of surfaces with near-normal orientation to the incoming radiation. With the exception of slightly south-facing slopes, flat land has the greatest hot spot forming potential in the Northern Hemisphere resulting in potential superadiabatic lapse rate near the ground. The Racetrack Playa clearly meets this requirement; surrounding gently-sloping alluvial fans may serve as secondary "dust devil nurseries."

Sinclair (1969) finally pointed out that if surface obstructions or natural terrain

barriers present a significant obstacle to the prevailing wind, vortices whose size will depend on the size of the surface obstruction and the speed of the wind may be generated and shed downwind of the obstacle. The preference of dust devils to follow each other in similar paths was also noted by Sinclair (1969) who observed repeated dust devil formation downwind of an obstacle, and then migration along a dry wash. The paths of dust devils observed in Sinclair's survey showed that they were steered by prevailing winds which were influenced by topography.

The dolomite cliffs at the south end of the Racetrack Playa may provide interference with prevailing winds causing eddies to form. If the flat surface just beyond provides the necessary sensible heat gradient, rotating and rising plumes will be produced. The shape of the Racetrack Valley itself is analogous to the river valleys of greatest dust devil frequency observed by Sinclair (1969).

It is also possible that dust devils are spawned by hot spots in the darker (i.e., thermally conductive) low-angle alluvial fan to the playa's southwest. Once developed, a convective column would be forced towards the northeast by prevailing winds.

The coefficient of dynamic friction for rubber on dry concrete is 1.02; the coefficient of static friction for rubber against most solids varies from 1.0 to 4.0 (Lide, 1994), yet a dust devil can shove a pickup truck (see page 225). Considering the weight of such a vehicle, it is not inconceivable to imagine rock movement due to these dynamic thermals when conducive surface conditions exist. It is recommended that future observations of preferred origin localities and routes of dust devils be conducted in this basin.

Personal observations confirm the existence and virulence of summer wind events on the Racetrack. On July 23, 1996 a serious dust storm took place (see Figure 4.24,

page 119). Although the origin point of the thermal was not observed, several vortices formed and some coalesced to produce a significant pillar of swirling sediment. The source of the material was the Racetrack itself, which is a hard-baked surface of fine material, more difficult to dislodge than loose soil. From an observing distance of about 1 kilometer in the shelter of a vehicle, the range beyond the playa was totally obscured by the quantity of material forced into the air. Over a period of ten minutes, several separate whirlwinds were observed as they moved along the basin floor. At times the audible evidence of pebble-sized fragments being pelted against the metal car frame was alarming. Much of the airborne material was carried over the western mountain peaks, and probably deposited in Saline Valley. The intensity of this short-lived event was a dramatic testament to the power of wind.

The concurrence of conditions favoring dust devil development and a water-saturated playa are somewhat problematic. Yet it is not inconceivable that both requisites can exist simultaneously. Summer rains accompanying monsoon activity produce brief yet heavy periods of precipitation. The Racetrack's surrounding hydrologic basin encompasses approximately 180 square kilometers: Much of this area consists of permeable alluvial fan deposits through which water percolates rapidly, while the remainder is composed of solid igneous rock slopes that allow water to drain onto the valley floor. While initial surface cooling occurs after wetting, temperatures rapidly increase soon after clouds pass or dissipate, particularly on the low-albedo and relatively flat-lying alluvium. It is feasible that these flanking surfaces act as dust devil spawning grounds not long after a rain event, while the highly impermeable basin floor remains flooded. The lag time in the reestablishment of vortex-conducive conditions after a summer storm allows for the slip-

pery clay film to form on the playa. It is also possible that the three springs may occasionally produce enough output to at least partially flood the playa surface, independent of a rain event. If dust devils form on southern alluvial "heat islands" as postulated here, they may be steered onto the saturated lake bed, ultimately propelling the rocks.

To summarize, rocks have a history of erratic motion on the Racetrack Playa. The lack of spatial order as recorded by this survey suggests a variety of driving mechanisms need to be considered. Although it is possible that ice rafts may sometimes or locally induce organized, tandem motion of rocks, evidence for this technique was rarely found, and was limited in geographic range. There is ample evidence that high wind velocities and dust devil activity aided by unique surface slickness characteristics may explain the overwhelming number of trails found in July 1996. Sharp and Carey (1976) recorded the movement of some rocks and stasis of others although the specimens were closely spaced. The non-uniformity of motion was explained as the work of local wind gusts (Sharp and Carey, 1976), but the trail routes witnessed in July 1996 suggest whirlwind activity as well. Since trails persist for only a few years at most, future comparisons to the data collected by this survey will need to be conducted before any definitive conclusions can be made.

Furthermore, although it is the least conducive time for field work, summer studies of dust devil incidence in the Racetrack may provide more evidence to this mystery, and in fact may allow for the first personal observations of a sliding rock event.

Chapter 8

Conclusions

“Geologists base many of their most far-reaching deductions on evidence obtained *after the fact* and without the possibility of laboratory duplication, or observation of the process in action. The moving stones present a geological problem susceptible of both.” (Bradley, 1963)

The Racetrack Playa has been the focal point of casual observations and formal scientific inquiry for nearly a century. Despite the extensive work conducted most notably by Kirk (1952), Stanley (1955), Sharp and Carey (1976) and by Reid et al. (1995) the causative conditions promoting the sliding rocks' motions remain unclear.

At the outset this project was conceived and designed in hopes of revealing predictable order in the sliding rock trails. The patterns have been successfully captured for the first time to high accuracy standards, and they do indeed show general trends. Yet the degree of chaotic motion implied by the furrows, and the insignificant correlations of rock and trail parameters, are remarkable. Perhaps the most surprising outcome of this research is the unanticipated *lack* of order in this natural system. Countless efforts to establish statistically significant relationships between rocks, trails and terrain characteristics yielded disappointing results. However, this in itself may be considered one of the project's accomplishments. Despite the unusual, sometimes apparently random patterns observed,

this research has contributed much to the understanding of the Racetrack's sliding rock phenomenon. Perhaps given more time and additional observations, the questions would be resolved.

8.1 Establishment of a Baseline

Among this project's achievements is the construction of the first complete, high-accuracy database of rock positions, descriptions and trail characteristics (as of July 1996). Visual records and locational data of this research are on file at Death Valley's Resources Management Division Headquarters; selected data are also available over the Internet. Hard copies of individual trail maps and rock identities are found in Appendix I. Any future studies of Racetrack activity will rely on the existence and availability of this archive. The identifying photo library facilitates the future monitoring of sliding rock activity without the need for permanent markings on the rocks, a practice formerly exercised by previous researchers, although never condoned by the National Park Service. As a baseline for comparison, changes in rock positions and trail data may be input directly to a Geographic Information System (GIS) using this survey's map as a control.

With over 10,000 coordinates (defining the vertices of every sliding rock trail) recorded to an accuracy of approximately 30 centimeters, this data set represents the most exhaustive and complete survey ever conducted of this phenomenon. Subsequent quantitative analyses revealed any and all relationships between rock parameters, trail characteristics and terrain elements.

8.2 A Record of Order and Chaos

Where it was initially hypothesized that trail character is intrinsically related to

rock size, rock shape and/or lithology, this survey has established that it is decidedly not. Among the surprising results, this research demonstrates that neither trail length nor trail straightness are appreciably related to rock size, except when spatially-bound subsets of the data are excluded (discussed below).

While there is a trend for large rocks to produce shorter trails, when the two fields are plotted their resulting correlation coefficient is insignificant. When rock volume is compared to the number of turns per trail, it is evident that there is a *tendency* for large rocks to produce straighter trails, but the two fields are only weakly related.

Neither a rock's degree of extension into the atmospheric boundary layer, nor its footprint on the playa significantly affects its traveled route. Rock motion appears to be only slightly affected by rock shape, if there exists a relationship at all.

Regularity emerges when considering only limited sections of the lake bed individually. Placement of rocks on the playa and trail patterns are clearly *not* isotropic. Since most rocks match the lithology of the cliff face at the playa's south end, the cliff face is their probable source. Yet once these fragments tumble onto the mud flats, their repositioning to new locations is controlled by aeolian processes, with clear evidence of motion preferences to the north-northeast. This is not surprising given the generalized wind patterns of the region, and considering the forced flow of air through a prominent topographic channel to the playa's southwest.

This research discovered that trails closest to the center of the boulder field tend to be the most chaotic. Trails closer to the east end of the playa are produced by a strikingly-homogeneous group of small cobbles (76%), which represent only 31% of rocks on the playa's complete extent. These trails are generally longer and show a greater degree of

straightness than the majority of those scarring the Racetrack. This natural, geographically-isolated subgroup seems to be subject to straight-line winds, where more westerly counterparts near the playa's center are jostled erratically by turbulent winds. The formation of wind vortices is likely due to the convergence of natural air channels onto the central playa region, similar to documented patterns observed through urban wind corridors and along natural mountainous obstructions and islands.

Similarly, the impressive lengths of the trails in this subgroup are spatially controlled. This area's proximity to the three springs and to the topographic low of the nearly-flat lakebed suggests that it is most often wet and slick, either from collecting precipitation or hydrologically-induced saturation, or a combination of factors. Hence while contributing somewhat, trail character is not dependent exclusively on rock character.

Terrain aspects of surrounding viewsheds show statistical significance in influencing general trail headings. A preponderance of north-northeast trail segments corresponds to the abundance of east-southeast and west-northwest terrain elements. Hence, the Racetrack's bounding landforms may be at least as influential over rock propulsion as the physical nature of the playa surface and rocks themselves.

As per National Park Service regulations, long-term direct wind measurements cannot be logged on or around the Racetrack. Therefore, wind velocity may only be inferred. GIS analyses imply that air is funneled through two topographic saddles, resulting in intense gusts on the playa and high-turbulence zones at the junction of the two air-streams.

The Racetrack Playa, encompassing an area of 680 hectares, may best be recognized as an melange of micro-environments, each with its own surface characteristics

(microtopography, sediment composition, saturation sources, algal growth potentialities, solar absorption characteristics, local aerodynamics) and resulting range of rock-traction potentials. The sliding rock phenomenon owes its existence to a complex interaction of geography, lithosphere, hydrosphere and atmosphere. The likelihood of future events are dependent on the optimum combination of lubrication and wind climate, which vary considerably between each spatial domain.

8.3 Wind as the Motive Force

Most Earth particles are eroded by running water which acts as an efficient sorting medium. The agent responsible for sliding rock activity has proven to be indiscriminate of clast size or shape. While ice is noted for its ability to transport and deposit a range of unsorted particles, there is reason to believe that ice is not necessary for activity to occur on the Racetrack. Evidence supporting the existence of extensive ice rafting as proposed by Reid et al. (1995) was absent in the physical records left by the pre-July, 1996 sliding rock episode. The most convincing indication is found in congruent but converging trails, (Figure 7.8, page 210). The general lack of parallelism among trails supports independent, wind-induced motion.

Measurements taken on the Racetrack in December, 1997 revealed up to six-fold variations in simultaneous wind speeds between areas separated by less than 400 meters (Table 4.4, page 122). On the day of this wind survey, winds were fairly calm. Yet if such variation is common, then extreme gusts may be typical in highly localized areas of the playa on windier days.

Wind is a superlative sorting medium, typically capable of transporting only up to

sand-sized material. However, wind vortices have been shown (both naturally and experimentally) to have the competency to carry particles of a great variety of sizes. This enhanced ability is derived from the severe barometric pressure gradient typical of rotating winds. While straight wind speeds on the Racetrack may be compared to the 40 meter-per-second gusts common on Owens Lake (Bacon, Cahill and Tombrello, 1996), their intensity is probably enhanced by the Racetrack's increased elevation and topographic configuration. In addition, the likelihood of dust devil formation dramatically increases the capability of airflow-caused traction events, and rock activity independent of rock weight or shape.

Having experienced Death Valley wind events (most notably in July and December 1996) in which pebble-sized materials pelted the sides of the research vehicle, it is not difficult to imagine the local wind climate fostering even more dramatic effects. Given a near friction-free surface, as would be expected after a heavy rain or similar influx of water through runoff and subsurface flow, the Racetrack would most certainly be a dynamic place during strong wind events.

8.4 Final Remarks

The National Park Service policies supporting only nonintrusive studies of this and other wilderness areas are imperative and highly appreciated. It is recommended that follow-up studies be conducted, including DGPS map generation of future rock trails, wind tunnel studies and three-dimensional automated airflow modeling of the area. Long-term direct measurements of wind velocity in the area would be quite helpful, yet their impact may be too great for consideration by the National Park Service in the future. Such under-

takings were precluded in the present survey by budgetary and time constraints.

It is the conclusion of this research project that wind acting alone on a saturated, but not necessarily frozen playa surface is responsible for sliding rock activity. Saturation may be achieved after local precipitation events and/or as a result of ground water discharge through springs. The proliferation of cyanobacteria and the deposition of a fine clay film assist the process by establishing a remarkably low-friction surface. It is further concluded that rotating winds are likely contributors to the dislodging and incipient traction of rocks on the playa. Airflow is greatly influenced by the Racetrack's elevation, flatness and surrounding terrain configuration, which results in a great degree of sliding activity toward the north and the northeast. However, until researchers actually observe the rocks in action, the cause still remains controversial.

Appendix A
Precambrian and Paleozoic Stratigraphy of Death Valley

Table A1: Death Valley Regional Stratigraphy (after McAllister, 1956)

Geologic Age	Rock Formation (thickness)	Lithology	RTV**
Permian	Bird Springs Formation (135 m.)	Limestone, shale, limestone conglomerate	X
Mississippian and Pennsylvanian	Rest Springs Shale (135 m.)	Shale, siltstone, discoidal argillite concretions	X
Mississippian	Perdido Formation (200 m.)	Interbedded dolomite and shale	X
Mississippian	Tin Mountain Formation (100 m.)	Fossiliferous shale	X
Devonian	Lost Burro Formation (750 m.)	Massive dolomite, algal dolomite, thin sandy beds	X
Devonian and Silurian	Hidden Valley Dolomite (750 m.)	Massive dolomite	X
Ordovician	Ely Springs Dolomite (150 m.)	Dolomite	X
Ordovician	Eureka Quartzite (90 m.)	Quartzite	X
Ordovician	Pogonip Formation (565 m.)	Fossiliferous dolomite and shale	X
Upper Cambrian	Nopah Formation (1090 m.)	Shale and algal dolomite	X
Upper Cambrian	Racetrack Dolomite (120 m.)	Cherty, black dolomite	X
Middle Cambrian	Bonanza King Formation (1060 m.)	Massive algal limestone and dolomite, collapse breccias abundant	X

Table A1: Death Valley Regional Stratigraphy (after McAllister, 1956)

Geologic Age	Rock Formation (thickness)	Lithology	RTV**
Middle Cambrian	Carrara Formation (750 m.)	Shale and thin dolomite and limestone beds	
Lower Cambrian	Zabriskie Quartzite (275 m.)	Quartzite, locally conglomeratic	
Precambrian to Lower Cambrian	Wood Canyon Formation (600 - 900 m.)	Mixed sedimentary rocks: dolomite, siltstone, sandstone, quartzite, arkosic conglomerate.	
Precambrian	Stirling Quartzite (600 - 900 m.)	Siltstone and quartzite	
Precambrian	Johnnie Formation (600 m.)	Mixed sedimentary rocks: quartzite, dolomite, siltstone, & conglomerate	
Precambrian	Noonday Dolomite (600 - 900 m.)	Algal dolomite with cross bedded quartzite units	
Precambrian	Kingston Peak Formation (900 - 1200 m.)	sandstone and siltstones grade upward into conglomerate (diamictite)	
Precambrian	Beck Springs Dolomite (450 m.)	Dolomite, well laminated to massive, locally oolitic	
Precambrian	Crystal Springs Fm. (900 m.)	Basal arkosic conglomerate, sandstone; stromatolitic limestone, shale/ mudstone, and quartz sandstone	
Precambrian	Basement Complex	Granite gneiss	

****RTV - Indicates that these rock formations crop out in the Cottonwood Mountains in the vicinity of the Racetrack Valley within the drainage basins providing sediment to the Racetrack Playa.**

Appendix B
Data Collected by the Louis G. Kirk (1952) Surveys

Table B1: Types and Characteristics of Rocks Sampled (Kirk, 1952)

Number	Type of Material	Weight (lbs.)	Location		Observations
			Quad.	Dist. from rim (mi.)	
1	Limestone	3.5	SW	1.4	Oriented with least apparent wind resistance toward trail
2	Limestone	4.5	SW	0.2	Two rocks juxtaposed with N face of limestone 1/4" from S face of granitic rock, as if limestone has pushed granitic rock.
	Granite	2		1.3	
3	Granite	1	SW	0.2	Oriented with corner toward track. 22' S was limestone with trail going in opposite direction from this one's.
4	Limestone	60	SW	1.0	Oriented with corner toward track. Very rough, irregular shaped rock.
5	Limestone	66	SW	0.8	15-20 fragments surrounding the rock, especially to S. Playa surface disturbed for 7" to N of rock.
6	Limestone	603	SE	0.2	As evidenced by etching, the present S face had previously been imbedded in the playa surface to a depth of 3.5". Oriented with corner toward trail.
7	Limestone	230	SE	0.2	Oriented with corner toward trail.
8	Limestone	320	SE	0.1	Oriented with corner toward trail.
*	Granite	36	NE	0.03	Playa surface disturbed for 2.5" to N of rock.
10	Granite	47	NE	0.1	Present position only about 200 feet S of previous position.
11	Limestone	142	NE	0.9	6 or so fragments to S of rock.

Table B1: Types and Characteristics of Rocks Sampled (Kirk, 1952)

Number	Type of Material	Weight (lbs.)	Location		Observations
			Quad.	Dist. from rim (mi.)	
12	Quartz	8	NE	0.05	Oriented with corner toward trail. Playa surface pushed up in mound for 2" to N of rock.

Table B2: Surface Characteristics of Rocks Sampled (Kirk, 1952)

Number	Side(s) facing trail				Bottom			
	Dimensions (in.)		Shape	Nature	Dimensions (in.)		Shape	Nature
	H	W			H	W		
1	1.75	3	Rectangular	Vertical	5	4	Squarish	Flat, irregular
	4	8	Convex curve	Very sloping				
2*	1.5	4	Triangular	Vertical	4	4	Squarish	Flat, rough
2*	3	3	Triangular	Vertical	2	3	Rectangular	Convex, irregular
3	2	2.5	Triangular	Vertical	2.5	2	Triangular	Flat, smooth
	1.75	2.5	Triangular	Vertical				
4	9	10	Triangular	Vertical	10	10	Irregular	Very rough and jagged, with 4-5" depression in center
	9	10	Rectangular	Vertical				
5	6	13	Rectangular	Vertical	9	14	Rectangular	Rough with 3.5" projection in center

Table B2: Surface Characteristics of Rocks Sampled (Kirk, 1952)

Number	Side(s) facing trail				Bottom			
	Dimensions (in.)		Shape	Nature	Dimensions (in.)		Shape	Nature
	H	W			H	W		
6	13	27	Rectangular	Vertical	24	18	Rectangular	Flat, rough
	12	18	Irregular	Overhanging				
7	10	11.5	Irregular	Vertical	16	12.5	Irregular	Flat, rough
	10	12	Rectangular	Sloping				
8	17	21	Triangular	Vertical	19	11.5	Oval	Flat, rough
	13	16	Triangular	Vertical				
9	6	7	Rectangular	Slightly overhanging	14	8.5	Pentagon	Both convex and concave, smooth
	9	13	Rectangular	Sloping				
10	6	5	Squarish	Sloping	12	9	Irregular	Flat, smooth
11	10	12	Irregular	Overhanging	12	11.5	Squarish	Slightly convex, smooth
12	3	8	Irregular	Vertical	8	6.5	Irregular	Flat, rough
	4	6.5	Rectangular	Vertical				

*Limestone

**Granite

Table B3: Characteristics of Trails on Racetrack Playa (Kirk, 1952)

Number	Usual Width (in.)	Usual Depth (in)	Total	Apparent General Course	Observations
1	8	Negligible	34	N 10° W	Dim as if quite weathered. Irregular sides with width varying from minimum 3" to maximum 8".
2	10	Negligible	70	N	Indistinct at inception. Varies in width from minimum of 3" to maximum 20".
3	2.5	0.25	50	Slight curve, N	Very distinct. Even-sided.
4	10	0.5	60	N	Ridge in center parallel to sides corresponding in height and position to depression in bottom face of rock.
5	12	Evidenced more by raised mud curls than smoothing or depression	14 2	W, 14'--N 20° W, 128'	Indistinct as though very weathered. Width varies from minimum of 11" to maximum of 29".
6	48	Negligible	60	N 45° W	2 very dim, but plainly discernable trails. One evidently made by number 6 and one by number 7 with no way to determine which is which.
	36	Negligible	90	N 35° E	
7	15	0.5	22 0	Slight curve, N 20° E	Very distinct. Even-sided.
8	10.5	1	86	S 50° W, 77'--S, 9'	Very distinct. Even-sided.

Table B3: Characteristics of Trails on Racetrack Playa (Kirk, 1952)

Number	Usual Width (in.)	Usual Depth (in)	Total	Apparent General Course	Observations
9	10	1	196	S 76° W, 3.4'--S 25° E, 10.6'--loop, 15.5'--curve, N 75° W, 29.3'--straight with jog, N 10° E, 35.5'--curve with jog, N 80° W, 11.7'--N 25° W, 4'--winding curve, N 50° E, 85.5'	Very distinct. Even-sided. Terminal 85 feet showed evidence of rock having stopped in two places.
10	11	1	786	S 50° E, 331'--N 80° W, 10.5'--S 20° W, 13.5'--loop, 18'--W, 22'--straight with 2 short right-angle jogs. N 10° W, 36.5'--curve, N 80° W, 354'	Initial 331 feet are more weathered than remainder of trail, probably older. Rock evidently had stopped at end of 331' run, and also stopped twice in 18' loop.
11	18	0.5	61	N 20° W	Very distinct. Even-sided
12	4	0.25	317	N 35° E, 25'--gentle winding curve, S 15° E, 100'	Very distinct. Even-sided.

Appendix C
Data Collected by the Sharp and Carey (1976) Surveys

Table C1: Characteristics of Monitored Stones (Sharp and Carey, 1976).

Stone ID (group)	Shape	Dimensions (cm.)	Mass (kg.)	Lithology	When marked
A) Mary Ann	Rectangular	20x16.5x10	6.6	Syenite	5/68
B) Ruth <i>a</i>	Tabular	13x10x3.8	0.85	Dark gray dolomite	5/68
B) Ruth <i>b</i>	Irregularly angular	18x16.5x11	6	Dark dolomite	1/73
C) Sue	Angular	15x6.3x5	0.65	Gray dolomite	5/68
C) Sally	Irregular	12.7 diameter	1.0	Light carbonate	5/68
C) Val	Pyramidal	7.5x5x2.5	0.18	Dark gray dolomite	5/68
C) Marion	Irregularly angular	15x7.5x5	0.8	Dark gray dolomite	5/68
D) Ev	Tabular	25x18x9	5.9	Gray dolomite	5/68
D) Irene	Slab	33x15x5	2.8	Gray dolomite	5/68
E) Peggy <i>a</i>	Rhombohedral	18x10x10	4.55	Dark gray dolomite	5/68
E) Peggy <i>b</i>	Rough/rhombohedral	23x15x10	3.6	Dark gray dolomite	1/71
F) Jean <i>a</i>	Irregular	23x18x9	4	Dark gray dolomite	5/68
F) Jean <i>b</i>	Rectangular	23x13x10	4.5	Gray dolomite	1/71
G) Bep	Tabular	23x14x7.5	3.7	Light gray carbonate	5/68
G) Milly	Roughly tabular	14x10x5	1.25	Light gray dolomite	5/68
G) Gerry	Tabular	12x7.5x5	0.7	Buff dolomite	5/68

Table C1: Characteristics of Monitored Stones (Sharp and Carey, 1976).

Stone ID (group)	Shape	Dimensions (cm.)	Mass (kg.)	Lithology	When marked
G) Jane	Irregularly tabular	7.5x2.5x2.5	0.22	Buff-gray dolo- mite	5/68
G) Carmen	Angular	12x9x9	1.4	Dark gray dolo- mite	5/68
G) Margie	Irregularly angular	6.3x5x5	0.34	Discolored gray dolomite	5/68
H) Nancy	Irregular cobble	7.5 diameter	0.25	Syenite	5/68
I) Kristy	Rectangular	14x9x6.3	1.85	Dark gray dolo- mite	5/68
J) Karen	Rectangular	74x48x51	320 (calcu- lated)	Dark gray dolo- mite	5/68
K)Daphne <i>a</i>	Tabular	10x6.3x3.8	0.6	Dark gray dolo- mite	5/68
K)Daphne <i>b</i>	Triangular pyramid	10x10x9.5	1.7	Syenite	1/73
L) Helen	Rectangular	28x23x10	14.2	Dark gray dolo- mite	5/68
M) Clem	Irregularly angular	28x23x14	12.7	Dark gray dolo- mite	5/68
N) Alice	Rectangular	28x20x14	17.8	Syenite	5/68
O) Grace <i>a</i>	Angular	7.5x6.3x2.5	0.28	Dark gray dolo- mite	5/68
O) Grace <i>b</i>	Triangular	7.5x3.8x3.8	0.17	Syenite	1/73
R) Hortense	Irregular	28x20x19	13.2	Dark gray dolo- mite	1/71
S) Dottie	Angular	36x13x18	24.3	Dark gray dolo- mite	1/73
T) Enid	Rhombohe- dral	18x15x15	5.9	Dark gray dolo- mite	5/74

Table C1: Characteristics of Monitored Stones (Sharp and Carey, 1976).

Stone ID (group)	Shape	Dimensions (cm.)	Mass (kg.)	Lithology	When marked
X	Rectangular	7.5x7x5	0.43	Dark gray dolomite	5/68
XX	Rectangular	18x10x6.3	2.8	Syenite	1/71
XXX	Irregular	23x10x15	3.2	Syenite	1/71

Table C2: Movement of Monitored Stones (Sharp and Carey, 1976)

Stone ID (group)	Winter of 1968-1969 (m)		Winter of 1972-1973 (m)	Winter of 1973-1974 (m)	Cumulative (m)
A) Mary Ann	64.5		28.4	109.3	202.2
B) Ruth	0		1.1	53.4	54.5
C) Sue	0		0.5	24.1	24.6
C) Sally	0		0	23.5	23.5
C) Val	0		0	15.9	15.9
C) Marion	0		8.9	7.6	16.5
D) Ev	4.3		0	0	4.3
D) Irene	4.9		0	0	4.9
E) Peggy	1.8	(1970-1971) 45.1	0	Missing	46.9
F) Jean	40.9		0.3	89	130.2
G) Bep	0		0	5.8	5.8
G) Milly	0		0.6	20.6	21.2
G) Gerry	0		0.9	25.3	26.2
G) Jane	0		0	20.4	20.4
G) Carmen	0		8.1	3.4	11.5
G) Margie	0		0.9	32.6	33.5
H) Nancy	18.3		43	201	262.3
I) Kristy	0		3.4	107.5	110.9
J) Karen	0		0	0	0

Table C2: Movement of Monitored Stones (Sharp and Carey, 1976)

Stone ID (group)	Winter of 1968-1969 (m)		Winter of 1972-1973 (m)	Winter of 1973-1974 (m)	Cumulative (m)
K) Daphne <i>a</i>	12.4		38	168.2	218.6
L) Helen	0		25.3	84.5	109.8
M) Clem	0		27.4	17.7	45.1
N) Alice	21.6		31.2	99.5	152.3
O) Grace <i>a</i>	15.2		3.9	72.3	91.4
R) Hortense		<u>1970-1971</u> 250	0	0	250
S) Dottie		<u>1971-1972</u> 61		0	61
T) Enid				86.5	86.5
X	8.5		0.6	4.6	13.7
XX			0	3.7	3.7
XXX			0	0	0

Appendix D
Calculated Friction Coefficients for Sharp and Carey's (1976) Monitored Stones
(After Bacon, Cahill and Tombrello, 1996)

Table D1: Threshold Coefficient of Friction (S_T) for Moving Rocks on Racetrack Playa (Bacon, Cahill and Tombrello, 1996)

Stone Identity	Stone Name	Length (cm.)	Width (cm.)	Height (cm.)	Mass (kg.)	Area/ Mass (m ² /kg)	S_T 80%	S_T 100%
A	Mary Ann	20	16.5	10	6.6	0.0028	.15	.23
B(a)	Ruth (a)	13	10	3.8	0.85	0.0051	.28	.43
B(b)	Ruth (b)	18	16.5	11	6	0.0032	.17	.27
C(1)	Sue	15	6.3	5	0.65	0.0075	.40	.63
C(3)	Val	7.5	5	2.5	0.18	0.0085	.46	.72
C(4)	Marion	15	7.5	5	0.8	0.0066	.36	.56
D(1)	Ev	25	18	9	5.9	0.0032	.17	.27
D(2)	Irene	33	15	5	2.8	0.0040	.21	.34
E(a)	Peggy (a)	18	19	19	4.55	0.0029	.16	.25
E(b)	Peggy (b)	23	15	10	3.6	0.0052	.28	.44
F(a)	Jean (a)	23	18	9	4	0.0046	.25	.39
F(b)	Jean (b)	23	13	10	4.5	0.0038	.21	.32
G(1)	Bep	23	14	7.5	3.7	0.0036	.20	.31
G(2)	Milly	14	10	5	1.25	0.0047	.26	.40
G(3)	Gerry	12	7.5	5	0.7	0.0068	.37	.57
G(4)	Jane	7.5	2.5	2.5	0.22	0.0049	.27	.42
G(5)	Carmen	12	9	9	1.4	0.0067	.36	.56
G(6)	Margie	6.3	5	5	0.34	0.0083	.45	.70
I	Kristy	14	9	6.3	1.85	0.0038	.21	.32
J	Karen	74	48	51	320	0.0009	.05	.08

Table D1: Threshold Coefficient of Friction (S_T) for Moving Rocks on Racetrack Playa (Bacon, Cahill and Tombrello, 1996)

Stone Identity	Stone Name	Length (cm.)	Width (cm.)	Height (cm.)	Mass (kg.)	Area/ Mass (m ² /kg)	S_T 80%	S_T 100%
K(a)	Daphne (a)	10	6.3	3.8	0.6	0.0050	.27	.42
K(b)	Daphne (b)	10	10	9.5	1.7	0.0056	.30	.47
L	Helen	28	23	10	14.2	0.0018	.10	.15
M	Clem	28	23	14	12.7	0.0028	.15	.24
N	Alice	28	20	14	17.8	0.0019	.10	.16
O(a)	Grace (a)	7.5	6.3	2.5	0.29	0.0059	.32	.50
O(b)	Grace (b)	7.5	3.8	3.8	0.11	0.0184	1.00	1.56
R	Hortense	28	20	19	13.2	0.0034	.18	.29
S	Dottie	36	13	18	24.3	0.0016	.09	.14
T	Enid	18	15	15	5.9	.0042	.23	.35
X	<i>unnamed</i>	7.5	7	5	0.43	0.0084	.46	.71
XX	<i>unnamed</i>	18	10	6.3	2.8	0.0030	.16	.26

Appendix E

Table E1: Infrared Emissivity and Wind Data: Racetrack Playa, February 1996

Date	Stop	Location *		Time (PST)	IR (Sky) @ 0°(N)	IR (Playa)	Wind data, other notes
		Lat/Lon	UTM (zone 11)				
February 18, 1996	1	36°41'41"N 117°34'18"W	448937E 4061152N	9:45 am	-48.3°C	13.0°C	Wind under 2 mph
	2	36°41'44"N 117°34'16"W	448987E 4061239N	10:00 am	-50.4°C	15.3°C	"
	3	36°41'44"N 117°34'16"W	448987E 4061239N	10:15 am	-49.5°C	16.3°C	"
	4	36°41'54"N 117°34'11"W	449123E 4061543N	10:30 am	-50.1°C	16.1°C	"
	5	36°41'54"N 117°34'08"W	449199E 4061543N	10:45 am	-53.0°C	18.9°C	"
	6	36°41'48"N 117°33'51"W	449176E 4061566N	11:00 am	-50.1°C	21.5°C	"
	7	36°41'58"N 117°33'51"W	449604E 4061677N	11:15 am	-56.4°C	20.2°C	Walked back to car (stop 1) and back for lunch
				11:30 am	-56.8°C	18.4°C	
				11:45 am	-53.3°C	22.5°C	
				12:00 noon	-60.3°C	21.1°C	
				12:15 pm	-57.1°C	20.3°C	
				12:30 pm	-52.4°C	21.0°C	Sustained wind @ 4 mph from 90° (E)
	8	36°42'01"N 117°33'48"W	449679E 4061793N	12:45 pm	-53.6°C	21.2°C	Sustained wind @ 7 mph, 106° (SE)
	9	36°42'07"N 117°33'39"W	449892E 4061954N	1:00 pm	-51.5°C	23.3°C	Sustained wind @ 6 mph, 103° (SE)

Table E1: Infrared Emissivity and Wind Data: Racetrack Playa, February 1996

Date	Stop	Location* *subject to 100 m S/A error		Time (PST)	IR (Sky) @ 0°(N)	IR (Playa)	Wind data, other notes
		Lat/Lon	UTM (zone 11)				
February 18, 1996	10	36°42'00"N 117°33'15"W	450246E 4061748N	1:15 pm	-50.8°C	22.0°C	Sustained wind @ 10 mph, 120° (SE)
	11	36°41'47"N 117°33'15"W	450181E 4060922N	1:30 pm	-45.4°C	21.4°C	Calm
	12	36°41'32"N 117°38'27"W	450217E 4060380N	1:45 pm	-55.2°C	20.8°C	Sustained wind @ 4 mph, 135° (SE)
	13	36°41'17"N 117°33'26"W	450157E 4060053N	2:00 pm	-58.3°C	23.3°C	Wind @ 4 mph, 200° (SW)
	14	36°41'06"N 117°33'29"W	450157E 4060053N	2:15 pm	-63.5°C	23.0°C	Calm
				2:30 pm	-66.0°C	24.2°C	Calm
	15	36°40'49"N 117°33'12"W	450538E 4059467N	2:45 pm	-36.3°C	22.8°C	Increasing clouds, wind @ 2 mph, 220° (SW)
	16	36°40'45"N 117°33'09"W	450628E 4059443N	3:00 pm	-63.5°C	24.8°C	Clearing, calm winds.
	17	36°40'34"N 117°32'54"W	451002E 4059098N	3:15 pm	-61.1°C	19.5°C	Wind @ 4 mph, 225° (SW)
	18	36°40'33"N 117°32'57"W	450936E 4059051N	3:30 pm	-54.0°C	20.3°C	Calm
	19	36°40'32"N 117°33'00"W	450862E 4059036N	3:45 pm	-60.8°C	18.5°C	Calm
	20	36°40'24"N 117°32'45"W	451208E 4058764N	4:00 pm	-57.6°C	18.0°C	Wind @ 6 mph, 120° (SE)
	21	36°40'34"N 117°32'49"W	451133E 4059055N	4:15 pm	-56.2°C	14.4°C	Calm

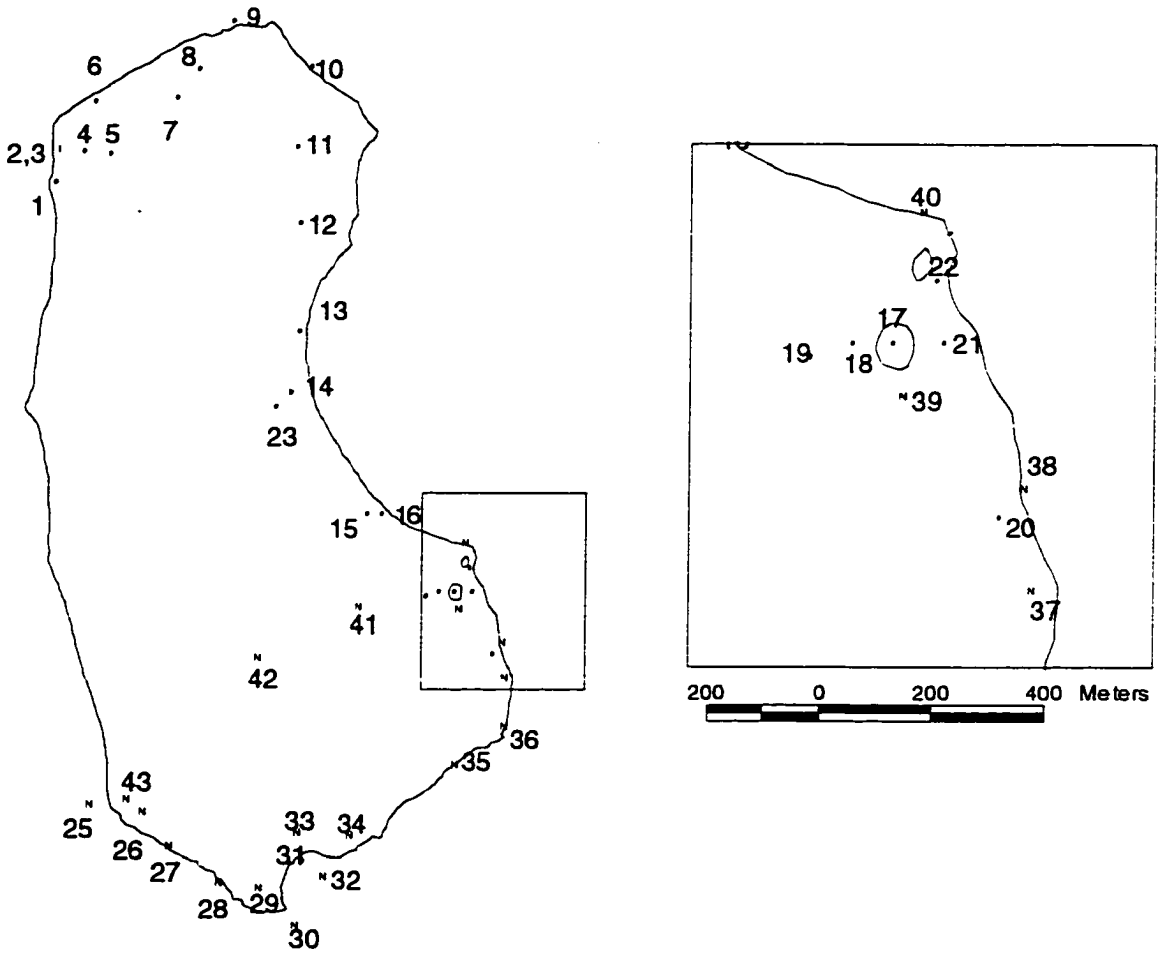
Table E1: Infrared Emissivity and Wind Data: Racetrack Playa, February 1996

Date	Stop	Location *		Time (PST)	IR (Sky) @ 0°(N)	IR (Playa)	Wind data, other notes
		Lat/Lon	UTM (zone 11)				
February 18, 1996	22	36°40'38"N 117°32'51"W	451079E 4059215N	4:30 pm	-51.1°C	12.7°C	Wind @ 4 mph, 220° (SE)
	23	36°41'02"N 117°33'31"W	450099E 4060015N	4:45 pm	-46.0°C	12.8°C	Calm
	24	? (Low battery level)		5:00 pm	-46.3°C	10.8°C	Wind @ 6 mph, 90° (E)
February 19, 1996	25	36°39'57"N 117°34'07"W	449175E 4057945N	9:15 am	-49.5°C	12.8°C	Wind @ 8 mph, 185° (S)
	26	36°39'56"N 117°33'57"W	449437E 4057909N	9:30 am	-35.0°C	15.5°C	Wind @ 8 mph, 185° (S)
	27	36°39'51"N 117°33'52"W	449558E 4057780N	9:45 am	-44.0°C	16.1°C	Wind @ 8-12 mph, 185° (S)
	28	36°39'46"N 117°33'41"W	449829E 4057612N	10:00 am	-29.5°C	15.4°C	Wind @ 7 mph, 170° (SSE)
	29	36°39'43"N 117°33'34"W	450009E 4057546N	10:15 am	-25.0°C	16.5°C	Wind @ 10 mph, 170° (SSE)
	30	36°39'39"N 117°33'26"W	450195E 4057366N	10:30 am	-20.4°C	20.0°C	Wind @ 5 mph, 140° (SE)
	31	36°39'49"N 117°33'24"W	450248E 4057712N	10:45 am	-26.0°C	18.2°C	Gusty wind, 0 - 10 mph, 220° (SW)
	32	36°39'48"N 117°33'21"W	450332 4057686N	11:00 am	-22.8°C	17.2°C	Turbulent, 8 mph, 160° (SE)

Table E1: Infrared Emissivity and Wind Data: Racetrack Playa, February 1996

Date	Stop	Location *		Time (PST)	IR (Sky) @ 0°(N)	IR (Playa)	Wind data, other notes
		Lat/Lon	UTM (zone 11)				
February 19, 1996	33	36°39'53"N 117°33'23"W	450288 4057802	11:15 am	-34.0°C	17.0°C	Highly variable wind, gusting to 25 mph, 220°
	34	36°39'53"N 117°33'15"W	450471E 4057808N	11:30 am	-28.3°C	19.5°C	Calm
	35	36°40'03"N 117°32'50"W	451105E 4058139N	11:45 am	-26.5°C	18.5°C	Wind @ 8 mph, 120° (SE)
	36	36°40'11"N 117°32'44"W	451255E 4058366N	12:00 noon	-32.6°C	17.8°C	Wind @ 7 mph, 170° (SSE)
	37	36°40'19"N 117°32'45"W	451254E 4058625N	12:15 pm	-28.0°C	16.8°C	Wind @ mph, 170° (SSE)
	38	36°40'25"N 117°32'45"W	451238E 4058797N	12:30 pm	-42.0°C	20.0°C	Wind @ 9 mph, 150° (SE)
	39	36°40'29"N 117°32'54"W	451025E 4058970N	12:45 pm	-32.5°C	20.2°C	Strong gusts!
	40	36°40'40"N 117°32'53"W	451044E 4059306N	1:00 pm	-37.0°C	18.8°C	Wind @ 8 mph, 160° (SE)
	41	36°40'32"N 117°33'02"W	450502E 4058990N	1:15 pm	-32.6°C	20.0°C	Extremely gusty winds, 180° (S)
	42	36°40'21"N 117°33'34"W	450004E 4058729N	1:30 pm	-28.8°C	19.2°C	Strong sustained winds with knocking gusts, 180° to 170° (S)
	43	36°39'58"N 117°34'00"W	449350E 4057996N	1:45 pm	-22.2°C	18.4°C	Wind @ 20 mph, 180° (S)

Figure E1: Infrared Emissivity and Wind Data Point Locations



Appendix F

Maps of Daily Surveys, July, 1996

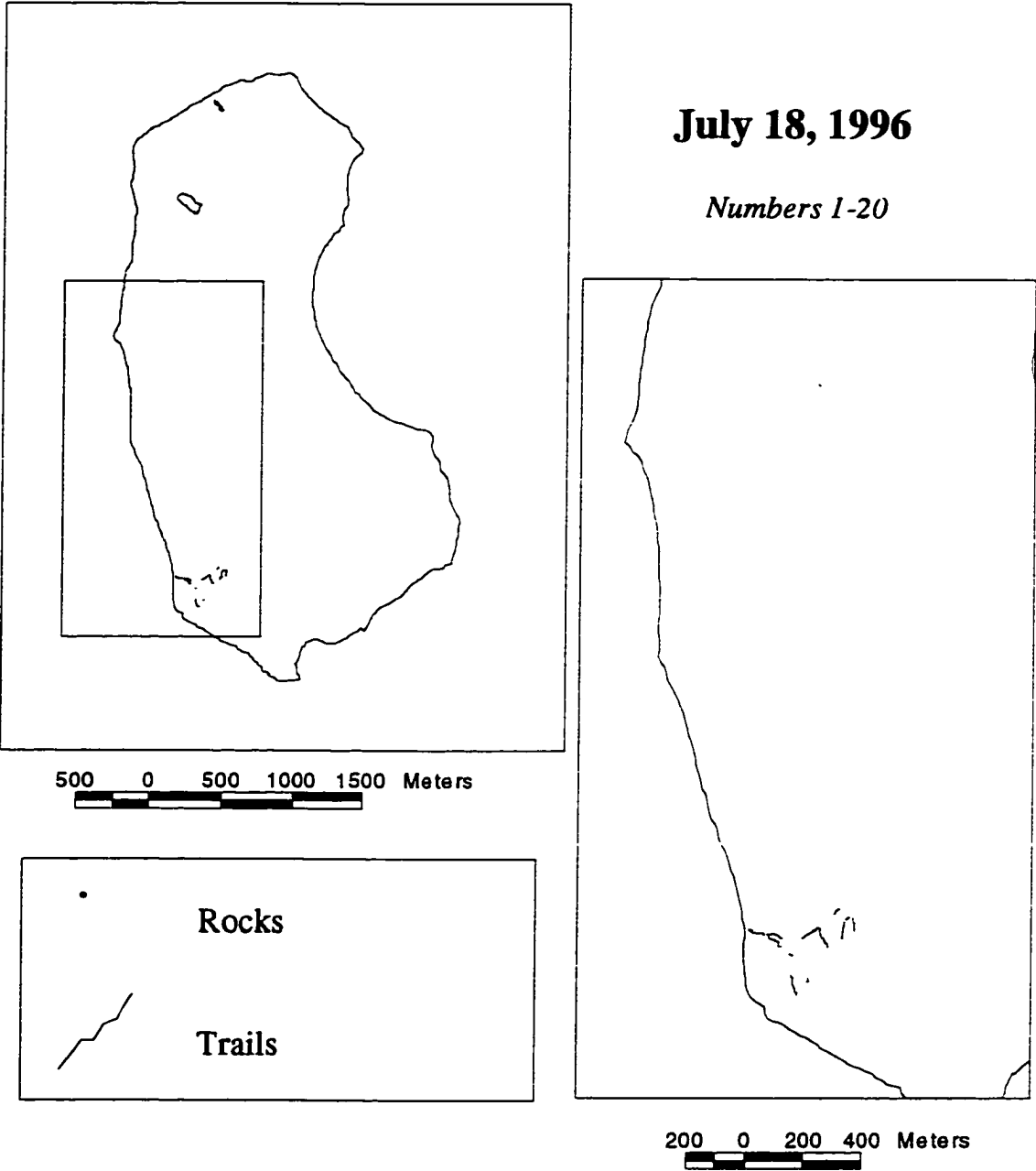


Figure F1: Western and northern rocks and trails (labeled 1 - 20) were recorded on the second day of GPS field mapping.

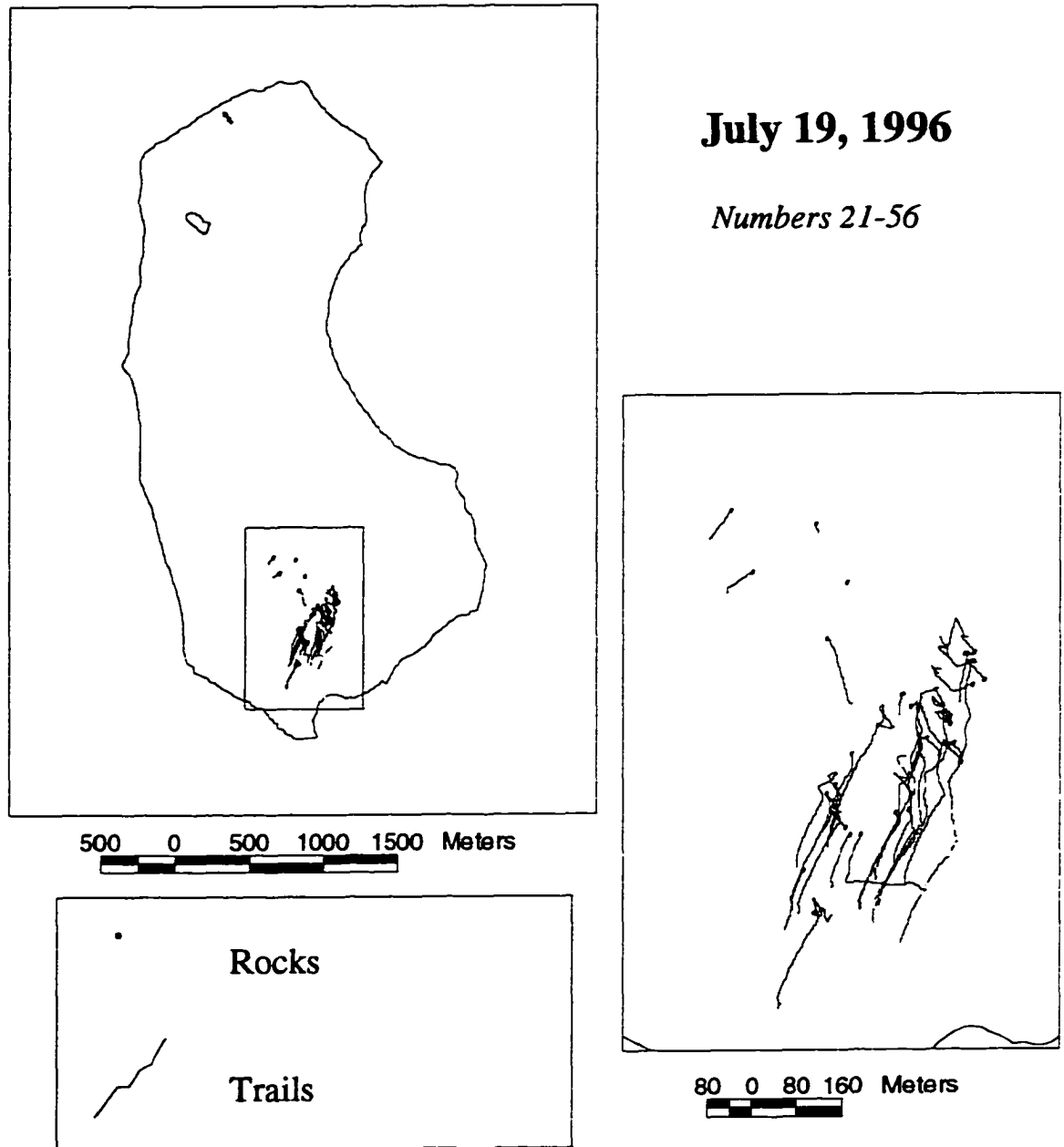


Figure F2: Rocks and trails numbers 21 - 56 were mapped on July 19, 1996.

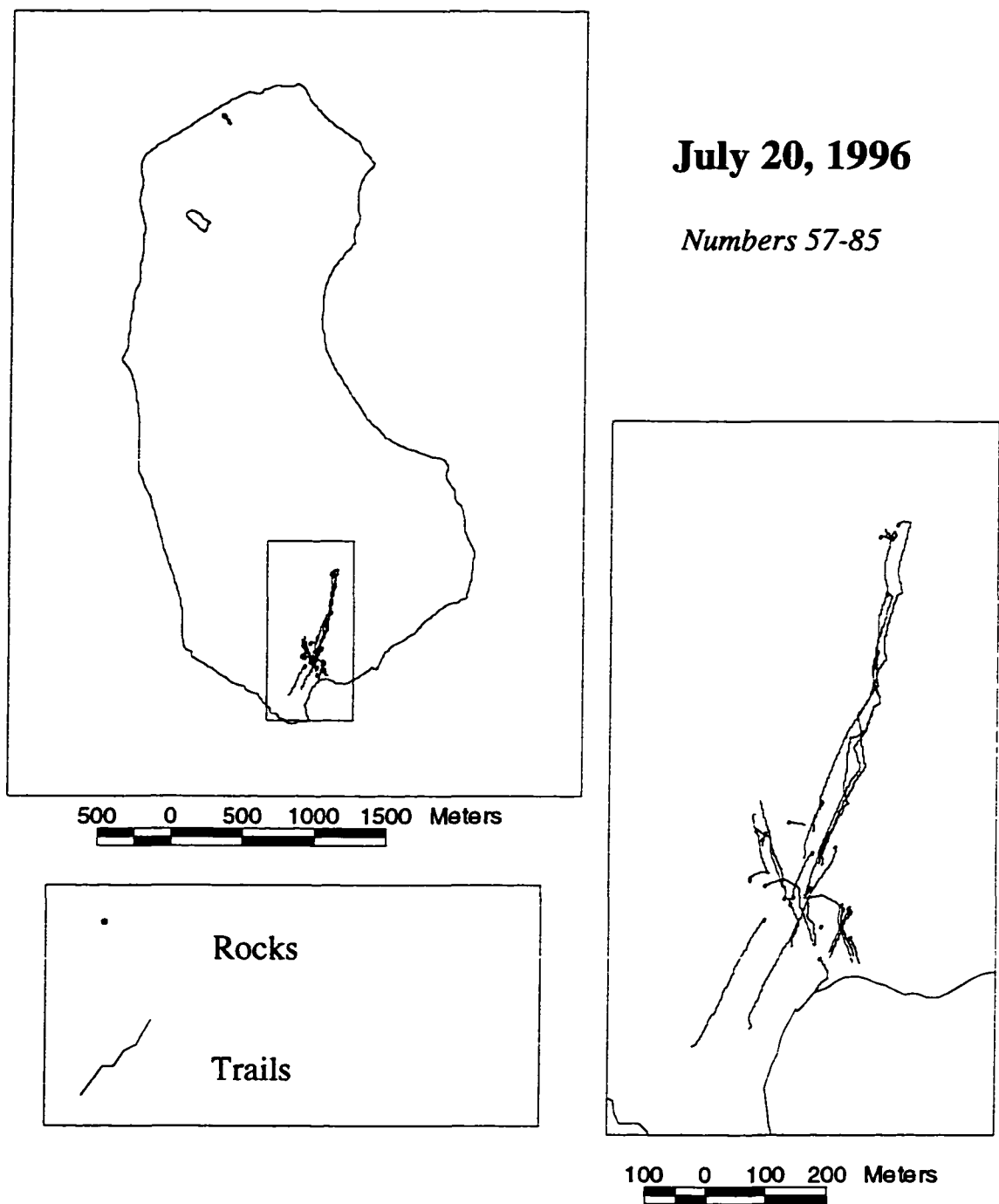


Figure F3: Rocks and trails numbers 57 - 85 were mapped on July 20, 1996.

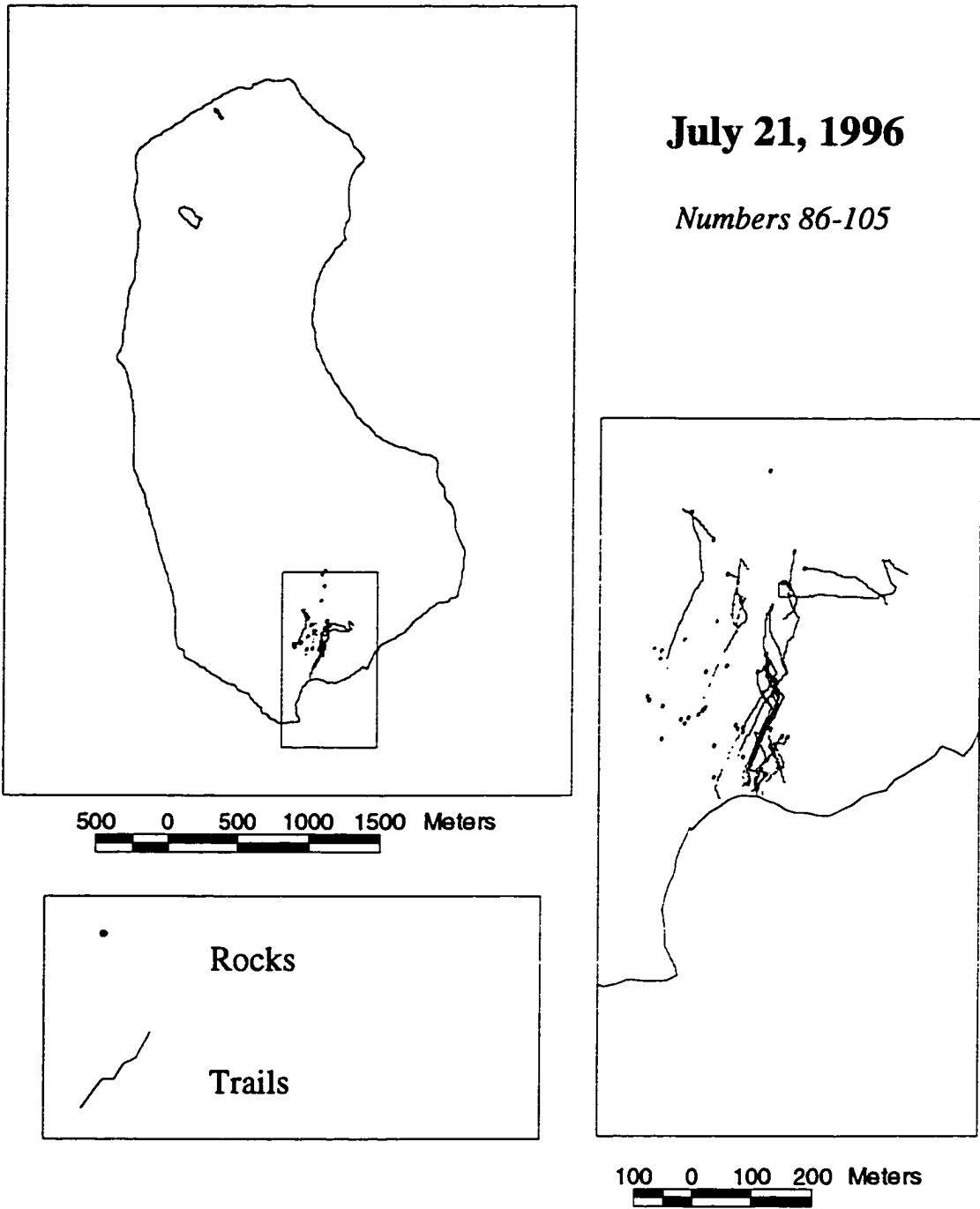


Figure F4: Rocks and trails numbers 86 - 105 were mapped on July 21, 1996.

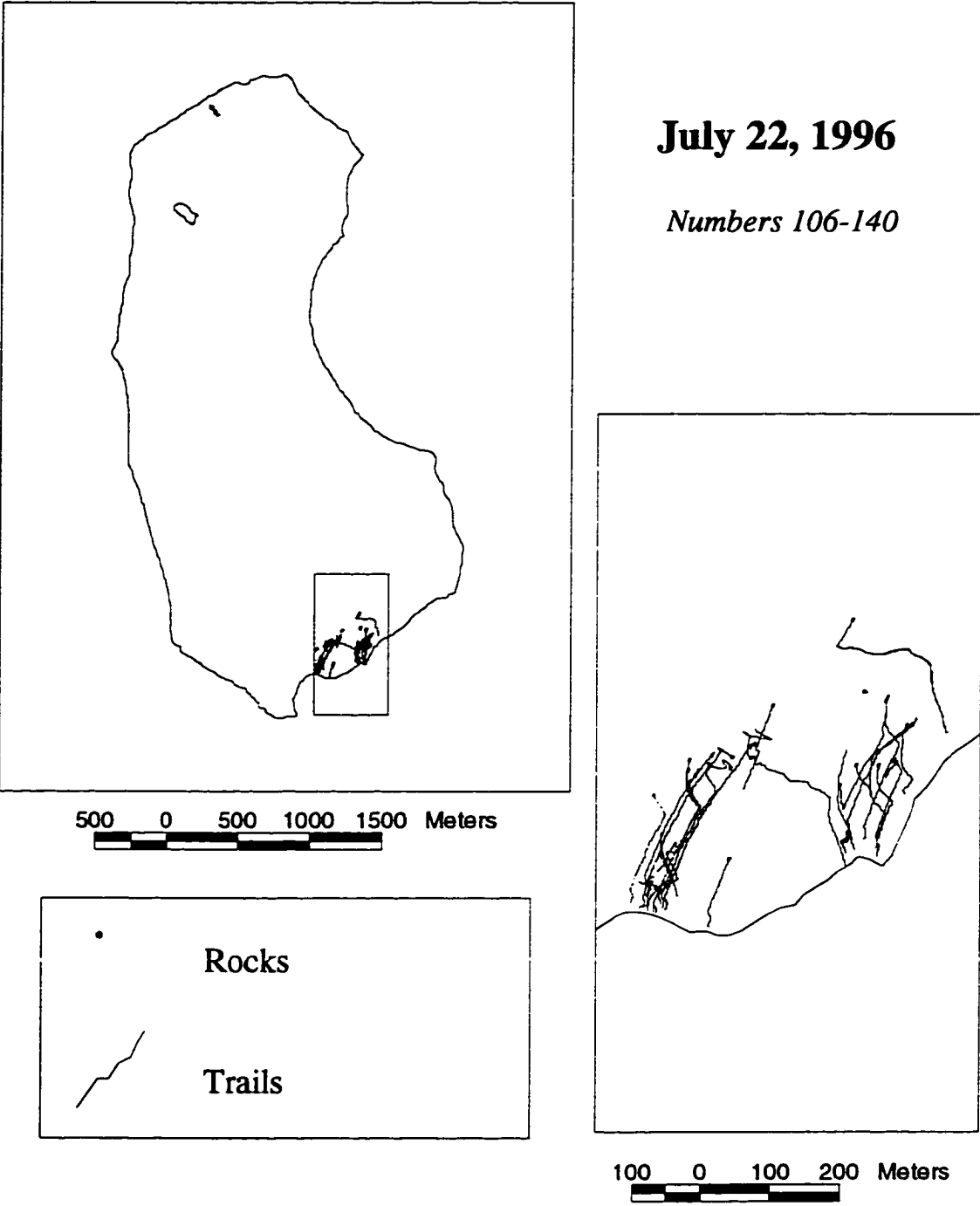


Figure F5: Rocks and trails numbers 106 - 140 were mapped on July 22, 1996.

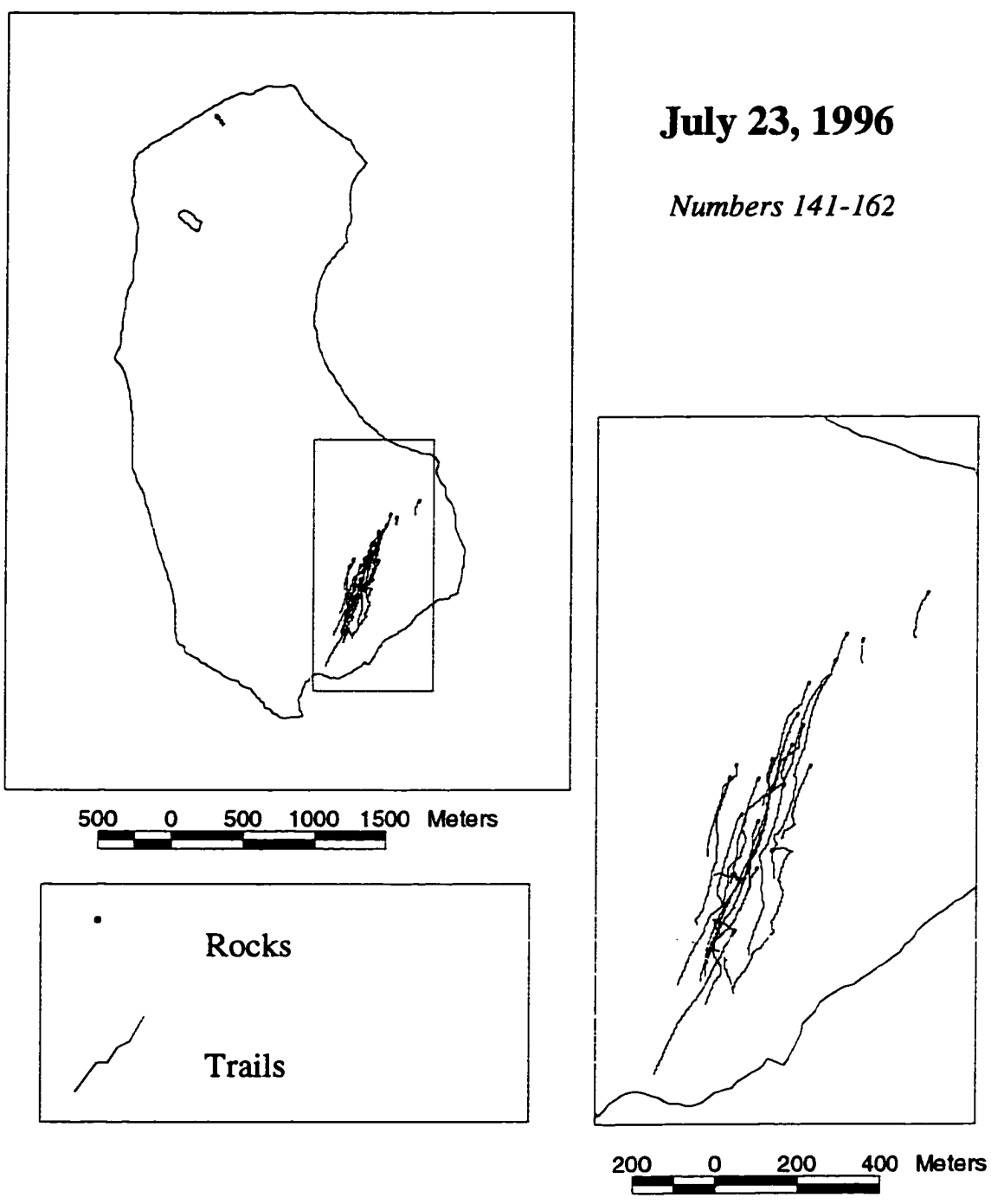


Figure F6: Capturing locational data for rocks and trails numbers 141-162 concluded the field work for the mapping project on July 23, 1996.

**Appendix G:
Racetrack Playa Rock and Trail Data, 1996**

Table G1: Lithology and Approximate Dimensions of Sliding Rocks, 1996

Rock Number/Name	Lithology	Height (cm.)	Length (cm.)	Width (cm.)	>Volume (cc)	Cube Root of >Volume
021 Stacy	carbonate	44	59	48	124608	49.948
022 Roberta	carbonate	12	30	10	3600	15.326
023 Violet	carbonate	7	20	15	2100	12.806
024 Virginia	carbonate	10	28	17	4760	16.822
025 XX	granite	7	16	11	1232	10.720
026 Johanna	carbonate	6	22	16	2112	12.830
027 Colette	carbonate	5	22	14	1540	11.548
028 Danette	carbonate	6	10	10	600	8.434
029 Michele	carbonate	11	35	23	8855	20.689
030 Theresa	carbonate	6	25	8	1200	10.627
031 Jacki	carbonate	9	13	13	1521	11.500
032 Amelia	carbonate	9	25	13	2925	14.301
033 Cynthia	carbonate	7	40	27	7560	19.626
034 Pamela	carbonate	10	25	22	5500	17.652
035 Ev	carbonate	9	27	20	4860	16.939
036 Jeannine	carbonate	15	20	15	4500	16.510
037 Mary	carbonate	15	25	20	7500	19.574
040 Fran	carbonate	17	20	20	6800	18.945
041a Thelma*	carbonate					
041b Louise*		10	25	15	3750	15.536
*two rocks traveled in tandem	carbonate	12	22	14	3696	15.461
042 Mona	carbonate	12	45	33	17820	26.120
043 Joanne	carbonate	5	14	10	700	8.879

Table G1: Lithology and Approximate Dimensions of Sliding Rocks, 1996

Rock Number/Name	Lithology	Height (cm.)	Length (cm.)	Width (cm.)	>Volume (cc)	Cube Root of >Volume
044 Robin	carbonate	6	20	10	1200	10.627
045 Karen	carbonate	36	68	56	137088	51.562
046 Clem	carbonate	14	26	23	8372	20.305
047 Peggy	carbonate	10	25	12	3000	14.422
048 MaryAnn	granite	10	19	17	3230	14.782
049 Edna	carbonate	22	45	32	31680	31.642
050 Alice	granite	14	27	20	7560	19.626
051 Barbara	carbonate	10	13	10	1300	10.914
052 Jennifer	granite	12	13	8	1248	10.766
053 Shirley	carbonate	18	22	12	4752	16.812
054 Janet	granite	7	15	10	1050	10.164
055 Julie	carbonate	7	16	12	1344	11.036
056 Lisa	carbonate	5	18	8	720	8.963
057 Susan	carbonate	13	40	15	7800	19.832
058 Rhonda	quartz monzonite	18	40	30	21600	27.850
059 Irene	carbonate	6	33	13	2574	13.705
060 Rebecca	carbonate	14	21	12	3528	15.223
061 Gabby	carbonate	7	28	22	4312	16.276
062 Clara	carbonate	6	18	8	864	9.524
063 Marietta	carbonate	29	43	43	53621	37.709
064 Xenio	carbonate	28	43	40	48160	36.383
068 Leslie	carbonate	12	22	20	5280	17.413
069 Sandra	granite	20	40	25	20000	27.144
070 Linda	carbonate	35	55	40	77000	42.543
072 Angel	carbonate	45	75	50	168750	55.260

Table G1: Lithology and Approximate Dimensions of Sliding Rocks, 1996

Rock Number/Name	Lithology	Height (cm.)	Length (cm.)	Width (cm.)	>Volume (cc)	Cube Root of >Volume
073 Claudia	carbonate	40	55	40	88000	44.480
074 Stefanie	granite	35	60	40	84000	43.795
075 Stella	carbonate	15	22	15	4950	17.043
077 Tammy	granite	26	45	33	38610	33.799
078 Lottie	carbonate	17	37	15	9435	21.131
079 Martina	carbonate	3	34	24	2448	13.477
080 Sheryl	carbonate	33	54	45	80190	43.123
081 Katie	carbonate	14	31	22	9548	21.215
082 Nicole	carbonate	22	35	20	15400	24.879
083 Eileen	carbonate	28	55	30	46200	35.882
084 Josephine	carbonate	3	22	15	990	9.967
085 Matilda	carbonate	25	33	28	23100	28.480
086 Patricia	carbonate	20	23	20	9200	20.954
087 Nilufer	carbonate	12	30	10	3600	15.326
088 Sherry	carbonate	25	30	19	14250	24.244
089 Bep	carbonate	8	23	12	2208	13.022
090 Glenda	carbonate	8	33	30	7920	19.933
091 Ellen	carbonate	19	35	23	15295	24.823
092 Ossie	carbonate	5	33	25	4125	16.038
093 Bessie	carbonate	20	28	24	13440	23.776
094 Kitty	carbonate	57	70	50	199500	58.432
095 Celia	carbonate	4	20	10	800	9.283
096 Marie	carbonate	20	26	14	7280	19.381
097 Laura	carbonate	11	24	20	5280	17.413
099 Margot	carbonate	6	19	15	1710	11.958
100 Chantal	carbonate	8	32	27	6912	19.049

Table G1: Lithology and Approximate Dimensions of Sliding Rocks, 1996

Rock Number/Name	Lithology	Height (cm.)	Length (cm.)	Width (cm.)	>Volume (cc)	Cube Root of >Volume
101 Elizabeth	carbonate	4	22	12	1056	10.183
102 Anne	carbonate	9	20	12	2160	12.927
103 Caroline	carbonate	10	30	15	4500	16.510
104 Betty	carbonate	8	38	28	8512	20.418
105 Wilma	carbonate	13	32	27	11232	22.395
106 Dottie	carbonate	14	34	19	9044	20.835
107 Trish	carbonate	8	33	19	5016	17.118
108 Rolanda	carbonate	11	23	14	3542	15.243
109 Margaret	carbonate	12	18	13	2808	14.108
110 Sara	carbonate	17	34	20	11560	22.611
111 Martha	carbonate	28	42	25	29400	30.864
112 Rosemarie	carbonate	10	30	28	8400	20.328
113 Sylvia	carbonate	17	30	17	8670	20.543
114 Minnie	carbonate	16	18	16	4608	16.641
115 Denise	carbonate	11	26	13	3718	15.492
116 Hortense	carbonate	15	33	17	8415	20.340
117 Lina	carbonate	10	22	15	3300	14.888
118 Sharon	carbonate	10	15	15	2250	13.104
119 Heather	carbonate	8	32	18	4608	16.641
120 Fortunata	carbonate	20	43	24	20640	27.431
121 Rose	carbonate	18	38	21	14364	24.309
122 Marlene	carbonate	3	17	12	612	8.490
123 Amanda	carbonate	9	55	44	21780	27.927
124 Rachel	carbonate	25	39	25	24375	28.994
125 Christine	carbonate	18	32	26	14976	24.649
126 Blanca	carbonate	8	24	18	3456	15.119

Table G1: Lithology and Approximate Dimensions of Sliding Rocks, 1996

Rock Number/Name	Lithology	Height (cm.)	Length (cm.)	Width (cm.)	>Volume (cc)	Cube Root of >Volume
127 Mamie	carbonate	7	46	28	9016	20.813
128 Carol	carbonate	4	12	10	480	7.830
129 Esther	carbonate	6	16	16	1536	11.538
130 Andrea	carbonate	21	30	25	15750	25.066
131 Brianna	carbonate	6	11	10	660	8.707
132 Goldy	carbonate	12	13	10	1560	11.598
133 Jill	carbonate	4	10	8	320	6.840
134 Molly	carbonate	10	26	25	6500	18.663
135 Hanna	carbonate	3	10	5	150	5.313
137 Carmina	carbonate	5	22	10	1100	10.323
138 Florence	carbonate	4	14	8	448	7.652
139 Agnes	carbonate	4	15	6	360	7.114
140 Debbie	carbonate	12	35	25	10500	21.898
141 April	granite	6	23	10	1380	11.133
142 Cindy	carbonate	3	12	8	288	6.604
143 Betsy	carbonate	8	22	17	2992	14.410
144 Milly	carbonate	6	13	11	858	9.502
145 Diane	carbonate	7	13	9	819	9.356
146 Dion	carbonate	5	14	7	490	7.884
147 Kristy	carbonate	7	16	8	896	9.641
148 Bonnie	carbonate	9	12	12	1296	10.903
150 Ryan	carbonate	5	20	12	1200	10.627
151 Allison	carbonate	6	27	13	2106	12.818
152 Carmen	carbonate	8	14	8	896	9.641
153 Layla	carbonate	5	18	12	1080	10.260
154 Marion	carbonate	4	14	10	560	8.243

Table G1: Lithology and Approximate Dimensions of Sliding Rocks, 1996

Rock Number/Name	Lithology	Height (cm.)	Length (cm.)	Width (cm.)	>Volume (cc)	Cube Root of >Volume
155 Aileen	carbonate	4	22	14	1232	10.720
156 Ruth	carbonate	12	17	16	3264	14.834
157 Alanis	carbonate	5	22	11	1210	10.656
158 Sophie	carbonate	8	23	18	3312	14.906
159 June	carbonate	3	13	10	390	7.306
160 Helen	carbonate	10	24	23	5520	17.673
161 Hillary	carbonate	23	30	20	13800	23.986
162 Tanya	carbonate	15	30	30	13500	23.811

Table G2: Racetrack Playa Sliding Rock Shapes

Rock Number/Name	Noses	Concavities	Rock Length (cm.)	Rock Width (cm.)	Aspect Ratio (L ÷ W)	Σ Noses + Concavities + Aspect Ratio
021 Stacy	4	0	59	48	1.229	5.229
022 Roberta	2	0	30	10	3.000	5.000
023 Violet	5	0	20	15	1.333	6.333
024 Virginia	4	0	28	17	1.647	5.647
025 XX	4	1	16	11	1.455	6.455
026 Johanna	4	0	22	16	1.375	5.375
027 Colette	4	0	22	14	1.571	5.571
028 Danette	4	0	10	10	1.000	5.000
029 Michele	3	0	35	23	1.522	4.522
030 Theresa	4	0	25	8	3.125	7.125

Table G2: Racetrack Playa Sliding Rock Shapes

Rock Number/Name	Noses	Concavities	Rock Length (cm.)	Rock Width (cm.)	Aspect Ratio (L+W)	Σ Noses + Concavities + Aspect Ratio
031 Jacki	3	0	13	13	1.000	4.000
032 Amelia	4	1	25	13	1.923	6.923
033 Cynthia	6	2	40	27	1.481	9.481
034 Pamela	4	0	25	22	1.136	5.136
035 Ev	5	2	27	20	1.350	8.350
036 Jeannine	4	0	20	15	1.333	5.333
037 Mary	4	1	25	20	1.250	6.250
040 Fran	0	0	20	20	1.000	1.000
041a Thelma*	4	0	25	15	1.667	5.667
041b Louise*		0	22	14	1.571	6.571
<i>*two rocks traveled in tandem</i>	5	0				
042 Mona	4	1	45	33	1.364	6.364
043 Joanne	4	0	14	10	1.400	5.400
044 Robin	3	0	20	10	2.000	5.000
045 Karen	4	0	68	56	1.214	5.214
046 Clem	3	0	26	23	1.130	4.130
047 Peggy	4	0	25	12	2.083	6.083
048 MaryAnn	5	0	19	17	1.118	6.118
049 Edna	4	1	45	32	1.406	6.406
050 Alice	4	0	27	20	1.350	5.350
051 Barbara	4	0	13	10	1.300	5.300
052 Jennifer	3	0	13	8	1.625	4.625
053 Shirley	4	0	22	12	1.833	5.833

Table G2: Racetrack Playa Sliding Rock Shapes

Rock Number/Name	Noses	Concavities	Rock Length (cm.)	Rock Width (cm.)	Aspect Ratio (L÷W)	Σ Noses + Concavities + Aspect Ratio
054 Janet	4	0	15	10	1.500	5.500
055 Julie	4	1	16	12	1.333	6.333
056 Lisa	4	0	18	8	2.250	6.250
057 Susan	4	0	40	15	2.667	6.667
058 Rhonda	1	1	40	30	1.333	3.333
059 Irene	5	0	33	13	2.538	7.538
060 Rebecca	4	0	21	12	1.750	5.750
061 Gabby	6	2	28	22	1.273	9.273
062 Clara	4	0	18	8	2.250	6.250
063 Marietta	0	0	43	43	1.000	1.000
064 Xenio	4	0	43	40	1.075	5.075
068 Leslie	3	0	22	20	1.100	4.100
069 Sandra	2	1	40	25	1.600	4.600
070 Linda	4	0	55	40	1.375	5.375
072 Angel	4	0	75	50	1.500	5.500
073 Claudia	4	0	55	40	1.375	5.375
074 Stefanie	3	1	60	40	1.500	5.500
075 Stella	3	0	22	15	1.467	4.467
077 Tammy	3	0	45	33	1.364	4.364
078 Lottie	4	0	37	15	2.467	6.467
079 Martina	3	0	34	24	1.417	4.417
080 Sheryl	4	1	54	45	1.200	6.200
081 Katie	4	0	31	22	1.409	5.409

Table G2: Racetrack Playa Sliding Rock Shapes

Rock Number/Name	Noses	Concavities	Rock Length (cm.)	Rock Width (cm.)	Aspect Ratio (L+W)	Σ Noses + Concavities + Aspect Ratio
082 Nicole	5	1	35	20	1.750	7.750
083 Eileen	4	1	55	30	1.833	6.833
084 Josephine	4	2	22	15	1.467	7.467
085 Matilda	5	0	33	28	1.179	6.179
086 Patricia	3	0	23	20	1.150	4.150
087 Nilufer	3	0	30	10	3.000	6.000
088 Sherry	3	0	30	19	1.579	4.579
089 Bep	4	0	23	12	1.917	5.917
090 Glenda	5	1	33	30	1.100	7.100
091 Ellen	3	1	35	23	1.522	5.522
092 Ossie	5	1	33	25	1.320	7.320
093 Bessie	5	1	28	24	1.167	7.167
094 Kitty	4	1	70	50	1.400	6.400
095 Celia	4	0	20	10	2.000	6.000
096 Marie	4	1	26	14	1.857	6.857
097 Laura	4	0	24	20	1.200	5.200
099 Margot	5	0	19	15	1.267	6.267
100 Chantal	5	2	32	27	1.185	8.185
101 Elizabeth	5	0	22	12	1.833	6.833
102 Anne	4	0	20	12	1.667	5.667
103 Caroline	2	0	30	15	2.000	4.000
104 Betty	5	1	38	28	1.357	7.357
105 Wilma	6	0	32	27	1.185	7.185

Table G2: Racetrack Playa Sliding Rock Shapes

Rock Number/Name	Noses	Concavities	Rock Length (cm.)	Rock Width (cm.)	Aspect Ratio (L+W)	Σ Noses + Concavities + Aspect Ratio
106 Dottie	6	1	34	19	1.789	8.789
107 Trish	4	1	33	19	1.737	6.737
108 Rolanda	5	0	23	14	1.643	6.643
109 Margaret	4	0	18	13	1.385	5.385
110 Sara	5	0	34	20	1.700	6.700
111 Martha	5	0	42	25	1.680	6.680
112 Rosemarie	5	1	30	28	1.071	7.071
113 Sylvia	4	0	30	17	1.765	5.765
114 Minnie	5	1	18	16	1.125	7.125
115 Denise	4	0	26	13	2.000	6.000
116 Hortense	5	0	33	17	1.941	6.941
117 Lina	4	0	22	15	1.467	5.467
118 Sharon	4	0	15	15	1.000	5.000
119 Heather	5	0	32	18	1.778	6.778
120 Fortunata	4	2	43	24	1.792	7.792
121 Rose	5	0	38	21	1.810	6.810
122 Marlene	4	0	17	12	1.417	5.417
123 Amanda	9	3	55	44	1.250	13.250
124 Rachel	4	1	39	25	1.560	6.560
125 Christine	3	0	32	26	1.231	4.231
126 Blanca	4	1	24	18	1.333	6.333
127 Mamie	5	0	46	28	1.643	6.643
128 Carol	5	0	12	10	1.200	6.200

Table G2: Racetrack Playa Sliding Rock Shapes

Rock Number/Name	Noses	Concavities	Rock Length (cm.)	Rock Width (cm.)	Aspect Ratio (L+W)	Σ Noses + Concavities + Aspect Ratio
129 Esther	4	1	16	16	1.000	6.000
130 Andrea	4	1	30	25	1.200	6.200
131 Brianna	5	0	11	10	1.100	6.100
132 Goldy	4	0	13	10	1.300	5.300
133 Jill	4	0	10	8	1.250	5.250
134 Molly	5	0	26	25	1.040	6.040
135 Hanna	4	0	10	5	2.000	6.000
137 Carmina	3	0	22	10	2.200	5.200
138 Florence	3	0	14	8	1.750	4.750
139 Agnes	4	0	15	6	2.500	6.500
140 Debbie	4	0	35	25	1.400	5.400
141 April	3	1	23	10	2.300	6.300
142 Cindy	4	0	12	8	1.500	5.500
143 Betsy	3	0	22	17	1.294	4.294
144 Milly	4	0	13	11	1.182	5.182
145 Diane	4	0	13	9	1.444	5.444
146 Dion	5	0	14	7	2.000	7.000
147 Kristy	4	0	16	8	2.000	6.000
148 Bonnie	4	0	12	12	1.000	5.000
150 Ryan	4	0	20	12	1.667	5.667
151 Allison	3	0	27	13	2.077	5.077
152 Carmen	4	0	14	8	1.750	5.750
153 Layla	4	0	18	12	1.500	5.500

Table G2: Racetrack Playa Sliding Rock Shapes

Rock Number/Name	Noses	Concavities	Rock Length (cm.)	Rock Width (cm.)	Aspect Ratio (L+W)	Σ Noses + Concavities + Aspect Ratio
154 Marion	4	1	14	10	1.400	6.400
155 Aileen	4	1	22	14	1.571	6.571
156 Ruth	5	0	17	16	1.063	6.063
157 Alanis	4	0	22	11	2.000	6.000
158 Sophie	4	1	23	18	1.278	6.278
159 June	4	0	13	10	1.300	5.300
160 Helen	5	1	24	23	1.043	7.043
161 Hillary	3	0	30	20	1.500	4.500
162 Tanya	5	0	30	30	1.000	6.000

Table G3: Observed Trail Characteristics of Selected Racetrack Rocks, 1996.

Rock Number/Name	Trail Width (cm.)	Total Length (m.)	Direct Length (m.)	Straightness
021 Stacy	25	49.279	21.522	0.437
022 Roberta	14	274.544	184.978	0.674
023 Violet	15	123.324	121.019	0.981
024 Virginia	21	80.603	78.936	0.979
025 XX	--	230.608	222.342	0.964
026 Johanna	11	315.913	132.368	0.419
027 Colette	12	256.688	246.025	0.958
028 Danette	--	339.558	218.127	0.642

Table G3: Observed Trail Characteristics of Selected Racetrack Rocks, 1996.

Rock Number/Name	Trail Width (cm.)	Total Length (m.)	Direct Length (m.)	Straightness
029 Michele	--	67.002	42.305	0.631
030 Theresa	12	365.139	326.048	0.893
031 Jacki	--	593.175	356.875	0.602
032 Amelia	10	574.469	320.992	0.559
033 Cynthia	25	379.008	257.650	0.680
034 Pamela	30	441.053	329.204	0.746
035 Ev	15	148.461	68.435	0.461
036 Jeannine	13	118.379	110.131	0.930
037 Mary	28	201.338	194.344	0.965
040 Fran	10	143.820	51.382	0.357
041 Thelma	10	110.068	108.200	0.983
042 Mona	22	240.956	152.854	0.634
043 Joanne	7	163.221	158.947	0.974
044 Robin	23	131.542	128.033	0.973
045 Karen	200	18.926	18.773	0.992
046 Clem	10	71.565	71.174	0.995
047 Peggy	20	66.222	61.989	0.936
048 MaryAnn	20	1.557	1.414	0.908
049 Edna	30	3.846	3.796	0.987
050 Alice	15	242.780	65.719	0.271
051 Barbara	10	142.459	93.106	0.654
052 Jennifer	10	107.790	56.101	0.520
053 Shirley	15	650.172	502.185	0.772
054 Janet	8	147.968	62.795	0.424
055 Julie	15	507.502	353.857	0.697

Table G3: Observed Trail Characteristics of Selected Racetrack Rocks, 1996.

Rock Number/Name	Trail Width (cm.)	Total Length (m.)	Direct Length (m.)	Straightness
056 Lisa	5	2.934	2.862	0.976
057 Susan	20	252.489	222.935	0.883
058 Rhonda	22	82.402	81.056	0.984
059 Irene	23	385.604	366.557	0.951
060 Rebecca	18	612.663	465.924	0.760
061 Gabby	25	640.371	587.520	0.917
062 Clara	12	563.367	529.498	0.940
063 Marietta	45	69.040	58.218	0.843
064 Xenio	--	8.806	8.642	0.981
068 Leslie	20	20.993	20.036	0.954
069 Sandra	20	248.684	246.716	0.992
070 Linda	35	412.179	193.432	0.469
072 Angel	40	140.214	105.933	0.756
073 Claudia	30	272.075	50.773	0.187
074 Stefanie	30	12.901	12.645	0.980
075 Stella	15	11.075	10.833	0.978
077 Tammy	40	186.395	181.872	0.976
078 Lottie	20	54.714	53.487	0.978
079 Martina	45	102.134	96.191	0.942
080 Sheryl	50	26.293	26.205	0.997
081 Katie	40	92.648	89.696	0.968
082 Nicole	35	1.577	1.562	0.991
083 Eileen	45	46.141	45.970	0.996
084 Josephine	35	83.939	83.691	0.997
085 Matilda	35	90.157	89.592	0.994

Table G3: Observed Trail Characteristics of Selected Racetrack Rocks, 1996.

Rock Number/Name	Trail Width (cm.)	Total Length (m.)	Direct Length (m.)	Straightness
086 Patricia	12	227.183	207.260	0.912
087 Nilufer	15	92.970	54.192	0.583
088 Sherry	23	121.002	98.776	0.816
089 Bep	20	280.640	227.525	0.811
090 Glenda	35	423.557	232.311	0.548
091 Ellen	25	333.858	203.697	0.610
092 Ossie	25	10.039	9.949	0.991
093 Bessie	30	77.793	63.140	0.812
094 Kitty	250	158.631	148.372	0.935
095 Celia	15	218.463	205.887	0.942
096 Marie	12	291.079	255.949	0.879
097 Laura	17	363.413	319.085	0.878
099 Margot	15	93.132	87.385	0.938
100 Chantal	27	62.712	60.497	0.965
101 Elizabeth	7	20.438	19.792	0.968
102 Anne	16	182.511	158.185	0.867
103 Caroline	26	95.158	47.164	0.496
104 Betty	35	187.965	174.354	0.928
105 Wilma	25	166.998	157.046	0.940
106 Dottie	25	177.081	164.234	0.927
107 Trish	22	96.462	94.708	0.982
108 Rolanda	8	88.344	79.515	0.900
109 Margaret	10	143.763	112.063	0.779
110 Sara	23	102.528	85.819	0.837
111 Martha	50	51.579	44.183	0.857

Table G3: Observed Trail Characteristics of Selected Racetrack Rocks, 1996.

Rock Number/Name	Trail Width (cm.)	Total Length (m.)	Direct Length (m.)	Straightness
112 Rosemarie	35	47.792	35.997	0.753
113 Sylvia	15	116.075	110.604	0.953
114 Minnie	25	239.927	222.652	0.928
115 Denise	--	222.231	206.481	0.929
116 Hortense	20	237.018	231.979	0.979
117 Lina	25	150.315	61.297	0.408
118 Sharon	12	318.617	236.835	0.743
119 Heather	18	276.605	238.625	0.863
120 Fortunata	40	274.418	268.733	0.979
121 Rose	39	120.093	44.929	0.374
122 Marlene	11	78.831	71.930	0.912
123 Amanda	50	326.883	262.485	0.803
124 Rachel	--	16.473	16.312	0.990
125 Christine	30	15.036	14.436	0.960
126 Blanca	10	204.132	195.331	0.957
127 Mamie	30	19.962	19.833	0.994
128 Carol	9	61.081	54.809	0.897
129 Esther	8	53.103	50.211	0.946
130 Andrea	24	248.021	152.492	0.615
131 Brianna	11	150.649	137.627	0.914
132 Goldy	8	126.315	124.042	0.982
133 Jill	7	29.601	28.919	0.977
134 Molly	15	63.056	61.376	0.973
135 Hanna	7	118.011	102.723	0.870
136 ?	20	255.607	206.615	0.808

Table G3: Observed Trail Characteristics of Selected Racetrack Rocks, 1996.

Rock Number/Name	Trail Width (cm.)	Total Length (m.)	Direct Length (m.)	Straightness
137 Carmina	10	247.766	228.599	0.923
138 Florence	11	216.665	201.574	0.930
139 Agnes	12	6.011	6.003	0.999
140 Debbie	20	305.441	219.261	0.718
141 April	12	131.498	121.646	0.925
142 Cindy	8	61.156	58.963	0.964
143 Betsy	12	789.523	764.977	0.969
144 Milly	8	661.879	633.820	0.958
145 Diane	7	880.731	842.506	0.957
146 Dion	7	414.333	404.746	0.977
147 Kristy	7	656.480	631.504	0.962
148 Bonnie	--	183.798	170.708	0.929
150 Ryan	8	208.463	197.251	0.946
151 Allison	15	343.407	328.343	0.956
152 Carmen	10	342.242	328.986	0.961
153 Layla	12	252.518	241.651	0.957
154 Marion	8	386.064	376.561	0.975
155 Aileen	15	476.769	456.595	0.958
156 Ruth	15	438.262	428.695	0.978
157 Alanis	15	286.919	273.304	0.953
158 Sophie	15	454.775	368.387	0.810
159 June	--	204.430	200.145	0.979
160 Helen	16	150.489	55.226	0.367
161 Hillary	18	220.948	136.895	0.620
162 Tanya	23	405.680	400.817	0.988

Table G4: Observed Locational Data for Selected Racetrack Playa Rock Trails, 1996

Rock Name/ Number	UTM Coordinates of Start Point		UTM Coordinates of End Point		Number of Mapped Points	Mapped Line Segments			
	X (Easting)	Y (Northing)	X (Easting)	Y (Northing)		Min. length (m.)	Max. length (m.)	Mean length (m.)	Standard Deviation
021 Stacy	450051.811	4057950.408	450032.669	4057960.246	25	0.123	2.625	1.971	0.680
022 Roberta	449954.325	4057780.149	450018.857	4057953.505	207	0.089	1.501	1.326	0.146
023 Violet	449966.702	4057917.329	449999.71	4058033.76	51	0.436	2.660	2.418	0.333
024 Virginia	449978.66	4057957.581	449999.794	4058033.635	35	0.090	2.625	2.303	0.497
025 XX	449977.363	4057960.433	450041.82	4058173.227	100	0.167	2.690	2.306	0.325
026 Johanna	449987.044	4058035.579	450057.383	4058147.712	137	0.291	2.684	2.306	0.516
027 Colette	449991.216	4057950.735	450057.318	4058187.714	107	0.141	2.888	2.399	0.384
028 Danette	450049.459	4058090.559	450130.571	4058293.044	146	0.088	2.716	2.326	0.525
029 Michele	450164.645	4058306.672	450169.699	4058348.674	36	0.075	2.604	1.861	0.681
030 Theresa	450125.8	4058009.167	450186.933	4058329.433	155	0.146	2.715	2.356	0.328
031 Jacki	450130.994	4057974.528	450255.069	4058309.14	252	0.293	3.045	2.354	0.452
032 Amelia	450099.908	4057956.29	450272.448	4058226.967	245	0.333	2.828	2.345	0.494
033 Cynthia	450174.903	4057999.956	450275.086	4058237.331	174	0.093	2.704	2.178	0.520

Table G4: Observed Locational Data for Selected Racetrack Playa Rock Trails, 1996

Rock Name/ Number	UTM Coordinates of Start Point		UTM Coordinates of End Point		Number of Mapped Points	Mapped Line Segments			
	X (Easting)	Y (Northing)	X (Easting)	Y (Northing)		Min. length (m.)	Max. length (m.)	Mean length (m.)	Standard Deviation
034 Pamela	450121.885	4057932.248	450236.389	4058240.897	186	0.037	2.767	2.371	0.464
035 Ev	450176.833	4058236.017	450185.59	4058168.145	74	0.082	2.528	2.006	0.575
036 Jeannine	450156.614	4058036.46	450183.317	4058143.305	50	0.243	2.695	2.368	0.494
037 Mary	450098.066	4057954.121	450160.524	4058138.155	83	0.313	2.738	2.426	0.434
040 Fran	450042.48	4058070.187	450073.965	4058110.793	63	0.360	2.738	2.283	0.559
041 Thelma	450048.407	4057996.727	450082.133	4058099.536	39	0.023	3.181	2.822	0.625
042 Mona	450213.08	4057990.315	450101.88	4058095.19	89	0.202	4.244	2.707	0.730
043 Joanne	450028.591	4058094.944	450086.489	4058242.971	63	0.021	3.025	2.591	0.571
044 Robin	450084.373	4058331.859	450039.459	4058451.756	50	0.034	3.079	2.631	0.742
045 Karen	450025.424	4058639.413	450021.54	4058657.78	10	0.059	2.691	1.893	1.050
046 Clem	449830.136	4058627.233	449871.518	4058685.14	29	0.006	2.980	2.468	0.890
047 Peggy	449861.836	4058532.398	449909.623	4058571.882	30	0.010	3.094	2.207	1.145
048 MaryAnn	450076.891	4058554.485	450077.46	4058553.191	4	0.017	1.450	0.389	0.613
049 Edna	450075.173	4058544.602	450073.186	4058547.836	4	0.024	2.219	0.961	0.840

Table G4: Observed Locational Data for Selected Racetrack Playa Rock Trails, 1996

Rock Name/ Number	UTM Coordinates of Start Point		UTM Coordinates of End Point		Number of Mapped Points	Mapped Line Segments			
	X (Easting)	Y (Northing)	X (Easting)	Y (Northing)		Min. length (m.)	Max. length (m.)	Mean length (m.)	Standard Deviation
050 Alice	450235.036	4058450.508	450296.29	4058426.698	99	0.014	3.148	2.452	0.728
051 Barbara	450268.246	4058330.647	450279.987	4058423.01	58	0.005	3.152	2.456	0.844
052 Jennifer	450246.403	4058436.139	450296.011	4058409.941	44	0.073	3.105	2.450	0.792
053 Shirley	450166.716	4057894.459	450312.773	4058374.935	232	0.012	3.201	2.802	0.572
054 Janet	450238.044	4058392.681	450295.982	4058368.466	62	0.004	3.089	2.387	0.854
055 Julie	450124.451	4057972.757	450248.619	4058304.113	185	0.011	3.315	2.743	0.643
056 Lisa	450251.938	4058296.691	450254.714	4058297.388	4	0.030	1.407	0.733	0.648
057 Susan	450108.769	4057655.888	450175.066	4057868.737	105	0.209	2.883	2.405	0.511
058 Rhonda	450180.05	4057878.892	450210.494	4057954.013	40	0.397	2.293	2.060	0.362
059 Irene	450221.986	4057933.83	450314.147	4058288.612	172	0.092	2.552	2.242	0.288
060 Rebecca	450222.946	4058025.157	450317.073	4058481.474	279	0.007	2.600	2.196	0.436
061 Gabby	450226.156	4057928.78	450343.965	4058504.367	235	0.017	3.037	2.725	0.428
062 Clara	450199.081	4057873.65	450328.745	4058387.026	203	0.092	5.247	2.775	0.563
063 Marietta	450215.911	4057719.572	450223.54	4057777.288	37	0.072	2.226	1.866	0.484

Table G4: Observed Locational Data for Selected Racetrack Playa Rock Trails, 1996

Rock Name/ Number	UTM Coordinates of Start Point		UTM Coordinates of End Point		Number of Mapped Points	Mapped Line Segments			
	X (Easting)	Y (Northing)	X (Easting)	Y (Northing)		Min. length (m.)	Max. length (m.)	Mean length (m.)	Standard Deviation
064 Xenio	450198.346	4057873.955	450198.384	4057882.597	7	0.018	1.855	1.258	0.652
068 Leslie	450166.049	4057896.46	450166.43	4057876.428	11	0.005	2.706	1.908	1.026
069 Sandra	450013.894	4057625.918	450132.842	4057842.066	88	0.090	3.057	2.826	0.440
070 Linda	450276.968	4057764.825	450136.379	4057897.681	147	0.082	3.299	2.804	0.470
072 Angel	450116.928	4058018.228	450111.039	4057912.459	54	0.553	2.919	2.597	0.481
073 Claudia	450125.124	4058042.039	450121.774	4057991.377	99	0.115	3.114	2.748	0.532
074 Stefanie	450130.16	4057963.369	450131.369	4057975.956	9	0.013	2.528	1.433	1.017
075 Stella	450130.836	4057976.708	450134.385	4057986.943	9	0.011	2.669	1.231	1.138
077 Tammy	450176.692	4057793.158	450246.819	4057960.966	77	0.319	2.650	2.421	0.339
078 Lottie	450212.225	4057986.146	450225.705	4058037.907	25	0.407	2.453	2.189	0.492
079 Martina	450195.392	4057945.845	450225.986	4058037.041	45	0.140	2.716	2.270	0.482
080 Sheryl	450199.629	4057998.781	450174.086	4058004.634	14	0.060	2.330	1.878	0.653
081 Katie	450278.642	4057778.019	450258.964	4057865.53	43	0.103	2.783	2.155	0.679
082 Nicole	450263.018	4057857.452	450262.68	4057858.977	3	0.100	1.141	0.526	0.445

Table G4: Observed Locational Data for Selected Racetrack Playa Rock Trails, 1996

Rock Name/ Number	UTM Coordinates of Start Point		UTM Coordinates of End Point		Number of Mapped Points	Mapped Line Segments			
	X (Easting)	Y (Northing)	X (Easting)	Y (Northing)		Min. length (m.)	Max. length (m.)	Mean length (m.)	Standard Deviation
083 Eileen	450287.477	4057765.281	450273.164	4057808.966	21	0.628	2.540	2.197	0.395
084 Josephine	450237.488	4057783.97	450271.861	4057860.276	34	1.187	2.724	2.469	0.248
085 Matilda	450237.016	4057772.747	450273.214	4057854.701	38	0.507	4.964	2.373	0.653
086 Patricia	450177.023	4057792.579	450267.169	4057979.208	102	0.641	2.615	2.227	0.477
087 Nilufer	450260.305	4058016.957	450267.705	4058070.641	46	0.123	3.745	2.021	0.748
088 Sherry	450260.692	4058019.398	450244.643	4058116.861	57	0.004	3.509	2.123	0.708
089 Bep	450205.317	4057905.476	450278.721	4058120.835	116	0.230	2.714	2.419	0.336
090 Glenda	450141.833	4057955.591	450220.694	4058174.107	187	0.272	2.908	2.265	0.526
091 Ellen	450540.408	4058113.527	450337.026	4058102.208	138	0.171	2.791	2.419	0.483
092 Ossie	450337.335	4058102.005	450345.578	4058096.434	7	0.122	2.365	1.434	0.876
093 Bessie	450336.197	4058038.051	450341.997	4058100.924	35	0.206	2.777	2.223	0.718
094 Kitty	450506.03	4058059.949	450372.562	4058124.761	68	0.214	2.851	2.333	0.395
095 Celia	450343.908	4057947.408	450354.656	4058153.014	88	0.319	2.773	2.483	0.365
096 Marie	450262.72	4057808.75	450317.029	4058058.871	120	0.163	2.745	2.426	0.426

Table G4: Observed Locational Data for Selected Racetrack Playa Rock Trails, 1996

Rock Name/ Number	UTM Coordinates of Start Point		UTM Coordinates of End Point		Number of Mapped Points	Mapped Line Segments			
	X (Easting)	Y (Northing)	X (Easting)	Y (Northing)		Min. length (m.)	Max. length (m.)	Mean length (m.)	Standard Deviation
097 Laura	450236.061	4057749.738	450315.738	4058058.715	153	0.244	2.755	2.375	0.364
099 Margot	450325.28	4057895.705	450310.991	4057981.914	39	0.357	2.678	2.388	0.474
100 Chantal	450332.616	4057912.744	450314.092	4057970.335	26	1.055	2.860	2.412	0.405
101 Elizabeth	450293.001	4057948.5	450308.057	4057961.347	12	0.102	2.126	1.703	0.626
102 Anne	450303.927	4057795.738	450296.483	4057953.748	74	0.154	2.820	2.466	0.480
103 Caroline	450322.197	4057892.846	450323.529	4057939.991	41	0.149	4.351	2.321	0.709
104 Betty	450280.452	4057761.11	450325.635	4057929.508	76	0.186	2.800	2.473	0.475
105 Wilma	450277.377	4057762.565	450318.657	4057914.089	68	0.290	2.744	2.456	0.387
106 Dottie	450271.776	4057757.118	450306.189	4057917.706	71	0.048	2.763	2.494	0.416
107 Trish	450340.63	4057769.127	450317.911	4057861.07	40	0.148	2.713	2.412	0.612
108 Rolanda	450281.726	4057790.062	450337.251	4057846.98	39	0.082	2.756	2.265	0.624
109 Margaret	450304.738	4057740.513	450345.636	4057844.846	64	0.131	2.713	2.246	0.508
110 Sara	450296.202	4057744.681	450316.323	4057828.108	47	0.343	2.786	2.181	0.665
111 Martha	450283.574	4057750.749	450302.647	4057790.603	24	0.119	2.704	2.149	0.626

Table G4: Observed Locational Data for Selected Racetrack Playa Rock Trails, 1996

Rock Name/ Number	UTM Coordinates of Start Point		UTM Coordinates of End Point		Number of Mapped Points	Mapped Line Segments			
	X (Easting)	Y (Northing)	X (Easting)	Y (Northing)		Min. length (m.)	Max. length (m.)	Mean length (m.)	Standard Deviation
112 Rosemarie	450289.73	4057751.011	450308.592	4057781.671	23	0.301	2.509	2.078	0.517
113 Sylvia	450382.534	4057720.382	450413.237	4057826.639	49	0.637	2.693	2.369	0.507
114 Minnie	450312.912	4057750.306	450357.003	4057968.549	97	0.058	2.724	2.473	0.338
115 Denise	450312.709	4057750.66	450353.61	4057953.049	85	0.520	2.880	2.614	0.344
116 Hortense	450290.132	4057773.619	450391.471	4057982.293	92	0.167	2.982	2.576	0.446
117 Lina	450370.043	4057894.246	450369.771	4057955.542	50	0.138	39.169	3.006	5.203
118 Sharon	450315.827	4057746.256	450417.354	4057960.226	133	0.242	2.860	2.396	0.553
119 Heather	450296.836	4057766.742	450417.354	4057972.697	109	0.130	2.839	2.538	0.452
120 Fortunata	450322.832	4057747.589	450444.602	4057987.15	109	0.476	3.089	2.518	0.319
121 Rose	450450.039	4058016.273	450443.761	4057971.785	51	0.078	3.432	2.355	0.597
122 Marlene	450433.64	4057921.605	450451.213	4057991.355	35	0.116	2.744	2.252	0.598
123 Amanda	450579.847	4057805.815	450476.819	4058047.235	132	0.227	2.780	2.476	0.390
124 Rachel	450578.938	4057843.648	450584.336	4057859.041	9	0.061	2.497	1.830	0.853
125 Christine	450583.687	4057845.204	450584.023	4057859.636	8	0.817	2.464	1.879	0.613

Table G4: Observed Locational Data for Selected Racetrack Playa Rock Trails, 1996

Rock Name/ Number	UTM Coordinates of Start Point		UTM Coordinates of End Point		Number of Mapped Points	Mapped Line Segments			
	X (Easting)	Y (Northing)	X (Easting)	Y (Northing)		Min. length (m.)	Max. length (m.)	Mean length (m.)	Standard Deviation
126 Blanca	450677.948	4058022.406	450581.956	4057852.289	86	0.068	4.617	2.374	0.474
127 Mamie	450581.106	4057823.203	450575.694	4057842.283	11	0.193	2.500	1.815	0.881
128 Carol	450583.12	4057988.675	450572.846	4057934.838	29	0.238	2.649	2.106	0.627
129 Esther	450615.797	4057914.988	450595.463	4057960.897	23	0.446	2.958	2.309	0.438
130 Andrea	450594.179	4057832.946	450625.515	4057982.184	102	0.500	3.750	2.432	0.391
131 Brianna	450625.65	4057824.225	450626.789	4057961.847	65	0.138	2.713	2.318	0.496
132 Goldy	450606.852	4057848.925	450645.648	4057966.744	55	0.013	2.701	2.297	0.489
133 Jill	450637.879	4057939.414	450651.435	4057964.959	14	0.722	2.431	2.114	0.424
134 Molly	450629.869	4057982.328	450675.908	4058022.916	29	0.679	2.528	2.174	0.535
135 Hanna	450664.617	4057917.92	450666.571	4058020.624	56	0.084	2.500	2.107	0.474
137 Carmina	450622.849	4057835.232	450640.252	4058063.168	113	0.088	2.642	2.193	0.469
138 Florence	450624.743	4057854.212	450638.132	4058055.341	92	0.836	4.543	2.355	0.394
139 Agnes	450610.339	4058067.016	450606.386	4058071.534	4	0.680	1.999	1.503	0.517
140 Debbie	450726.802	4058005.225	450589.675	4058176.315	145	0.577	2.469	2.106	0.413

Table G4: Observed Locational Data for Selected Racetrack Playa Rock Trails, 1996

Rock Name/ Number	UTM Coordinates of Start Point		UTM Coordinates of End Point		Number of Mapped Points	Mapped Line Segments			
	X (Easting)	Y (Northing)	X (Easting)	Y (Northing)		Min. length (m.)	Max. length (m.)	Mean length (m.)	Standard Deviation
141 April	450953.295	4058866.856	450985.158	4058984.255	53	0.058	3.040	2.481	0.672
142 Cindy	450820.805	4058806.191	450822.232	4058865.137	27	0.012	3.084	2.265	1.133
143 Betsy	450548.666	4058080.854	450756.054	4058817.183	260	0.043	3.310	3.037	0.345
144 Milly	450609.834	4058272.002	450783.327	4058881.615	220	0.041	5.945	3.009	0.523
145 Diane	450444.513	4057957.636	450693.654	4058762.462	359	0.055	9.809	2.453	0.907
146 Dion	450547.627	4058297.069	450664.058	4058684.707	166	0.322	4.029	2.496	0.514
147 Kristy	450444.202	4058068.535	450678.452	4058654.986	251	0.055	3.349	2.615	0.565
148 Bonnie	450582.016	4058451.48	450651.337	4058607.479	69	0.020	3.067	2.664	0.657
150 Ryan	450627.02	4058371.751	450695.986	4058556.553	82	0.014	3.245	2.542	0.892
151 Allison	450503.206	4058262.707	450606.578	4058574.353	124	0.011	3.139	2.769	0.686
152 Carmen	450484.326	4058206.647	450571.65	4058523.832	120	0.023	3.131	2.852	0.457
153 Layla	450448.172	4058327.345	450517.084	4058558.962	102	0.558	2.735	2.476	0.343
154 Marion	450420.932	4058157.209	450501.575	4058525.03	153	0.228	2.786	2.523	0.275
155 Aileen	450375.667	4058007.474	450531.369	4058436.701	185	0.370	3.705	2.577	0.370

Table G4: Observed Locational Data for Selected Racetrack Playa Rock Trails, 1996

Rock Name/ Number	UTM Coordinates of Start Point		UTM Coordinates of End Point		Number of Mapped Points	Mapped Line Segments			
	X (Easting)	Y (Northing)	X (Easting)	Y (Northing)		Min. length (m.)	Max. length (m.)	Mean length (m.)	Standard Deviation
156 Ruth	450430.975	4058014.978	450571.127	4058420.116	175	0.637	8.122	2.504	0.567
157 Alanis	450461.339	4058112.55	450571.073	4058362.857	112	0.193	2.797	2.562	0.369
158 Sophie	450510.676	4057995.391	450606.646	4058351.058	174	0.097	3.055	2.614	0.483
159 June	450473.507	4058126.539	450567.809	4058303.076	78	0.047	2.945	2.621	0.575
160 Helen	450465.35	4058282.589	450520.473	4058279.218	71	0.003	2.932	2.120	0.955
161 Hillary	450443.176	4058029.855	450516.224	4058145.632	91	0.304	3.107	2.428	0.506
162 Tanya	450321.246	4057787.048	450510.907	4058140.153	155	0.474	6.175	2.617	0.550

Table G5: Simplified Octants of Motion for Selected Racetrack Rock Trails, 1996

Rock Number/ Name	Number of Turns	Octants of Motion							
		0 (0° to 45°)	1 (46° to 90°)	2 (91° to 135°)	3 (136° to 180°)	4 (181° to 225°)	5 (226° to 270°)	6 (271° to 315°)	7 (316° to 360°)
021 Stacy	1	0	0	0	0	39	1	6	51
022 Roberta	5	346	1	1	64	5	11	20	99
023 Violet	3	212	0	0	0	0	0	0	33
024 Virginia	1	137	0	0	0	0	0	0	23
025 XX	2	351	0	0	0	0	0	0	109
026 Johanna	13	277	52	32	103	10	31	49	74
027 Colette	7	373	1	0	0	0	0	0	138
028 Danette	11	455	7	4	83	9	14	47	57
029 Michele	7	69	1	3	11	2	1	16	26
030 Theresa	12	500	0	0	0	15	14	1	198
031 Jacki	32	550	71	84	107	8	23	51	285
032 Amelia	26	582	53	69	209	4	6	25	193
033 Cynthia	20	446	27	62	58	1	9	21	125
034 Pamela	14	511	21	52	51	0	7	19	214
035 Ev	10	1	1	11	170	11	32	58	8
036 Jeannine	6	177	0	1	1	0	0	0	55
037 Mary	5	335	2	0	0	0	0	0	64
040 Fran	12	121	2	23	66	1	10	35	25
041 Thelma	1	195	0	0	0	0	0	0	24
042 Mona	22	164	0	0	0	0	116	171	27
043 Joanne	7	274	13	0	0	0	0	0	38
044 Robin	3	0	0	0	0	0	0	18	243

Table G5: Simplified Octants of Motion for Selected Racetrack Rock Trails, 1996

Rock Number/ Name	Number of Turns	Octants of Motion							
		0 (0° to 45°)	1 (46° to 90°)	2 (91° to 135°)	3 (136° to 180°)	4 (181° to 225°)	5 (226° to 270°)	6 (271° to 315°)	7 (316° to 360°)
045 Karen	0	0	0	0	0	0	0	0	36
046 Clem	0	141	0	0	0	0	0	0	0
047 Peggy	2	26	104	0	0	0	0	0	0
048 MaryAnn	0	0	0	0	1	0	0	0	0
049 Edna	0	0	0	0	0	0	0	0	6
050 Alice	19	133	5	98	153	9	30	40	12
051 Barbara	7	159	16	13	10	7	13	21	42
052 Jennifer	6	0	64	44	65	1	12	26	0
053 Shirley	20	773	33	49	73	0	15	48	305
054 Janet	13	0	84	47	93	6	5	29	25
055 Julie	26	532	98	39	70	1	13	62	193
056 Lisa	0	0	4	0	0	0	0	0	0
057 Susan	4	375	0	1	13	0	0	0	113
058 Rhonda	1	155	0	0	0	0	0	0	8
059 Irene	7	582	17	0	0	0	0	0	170
060 Rebecca	38	741	31	29	47	16	28	65	261
061 Gabby	21	917	19	0	0	0	23	19	299
062 Clara	18	847	66	3	0	0	0	15	193
063 Marietta	4	61	14	0	0	0	0	0	61
064 Xenio	3	4	0	0	0	0	0	0	12
068 Leslie	2	0	0	0	22	18	0	0	0
069 Sandra	1	483	13	0	0	0	0	0	0
070 Linda	19	52	0	0	117	54	109	132	357

Table G5: Simplified Octants of Motion for Selected Racetrack Rock Trails, 1996

Rock Number/ Name	Number of Turns	Octants of Motion							
		0 (0° to 45°)	1 (46° to 90°)	2 (91° to 135°)	3 (136° to 180°)	4 (181° to 225°)	5 (226° to 270°)	6 (271° to 315°)	7 (316° to 360°)
072 Angel	3	0	1	0	206	1	50	19	0
073 Claudia	9	25	0	0	292	22	0	50	153
074 Stefanie	1	18	0	0	0	0	0	0	6
075 Stella	1	19	1	0	0	0	0	0	0
077 Tammy	2	343	0	0	0	0	0	0	28
078 Lottie	3	92	0	0	0	0	0	0	16
079 Martina	5	178	0	2	3	0	0	0	20
080 Sheryl	0	0	0	0	0	0	0	51	0
081 Katie	8	32	0	0	0	0	0	0	151
082 Nicole	0	0	0	0	0	0	0	0	2
083 Eileen	0	0	0	0	0	0	0	0	91
084 Josephine	0	166	0	0	0	0	0	0	0
085 Matilda	1	176	0	0	0	0	0	0	3
086 Patricia	5	404	4	8	10	3	0	0	23
087 Nilufer	8	98	2	3	24	0	1	33	22
088 Sherry	8	123	0	0	0	6	2	38	69
089 Bep	4	400	16	1	43	0	0	0	99
090 Glenda	19	337	19	86	87	5	24	48	233
091 Ellen	22	24	15	13	90	19	173	283	46
092 Ossie	0	0	0	15	4	0	0	0	0
093 Bessie	9	47	37	0	0	0	1	7	61
094 Kitty	8	0	0	0	0	0	15	248	52
095 Celia	7	272	13	0	0	0	0	0	150

Table G5: Simplified Octants of Motion for Selected Racetrack Rock Trails, 1996

Rock Number/ Name	Number of Turns	Octants of Motion							
		0 (0° to 45°)	1 (46° to 90°)	2 (91° to 135°)	3 (136° to 180°)	4 (181° to 225°)	5 (226° to 270°)	6 (271° to 315°)	7 (316° to 360°)
096 Marie	4	391	0	1	7	4	2	0	175
097 Laura	11	559	0	0	4	16	1	1	144
099 Margot	3	78	0	0	0	0	0	0	107
100 Chantal	2	26	0	0	0	0	0	0	98
101 Elizabeth	1	10	29	0	0	0	0	0	0
102 Anne	9	144	2	14	0	0	0	0	203
103 Caroline	7	45	6	0	40	2	0	2	93
104 Betty	6	294	1	1	0	0	0	0	77
105 Wilma	2	276	0	0	0	0	0	0	56
106 Dottie	2	269	0	0	0	0	0	0	84
107 Trish	2	24	0	0	0	0	0	0	167
108 Rolanda	11	97	63	14	1	0	0	0	0
109 Margaret	11	111	48	30	0	0	0	2	94
110 Sara	6	69	44	0	0	0	0	0	90
111 Martha	3	57	26	0	0	0	0	0	19
112 Rosemarie	2	57	1	22	0	0	0	0	14
113 Sylvia	4	201	0	0	0	0	0	2	27
114 Minnie	3	370	0	0	0	0	0	0	108
115 Denise	5	333	0	0	0	0	0	0	110
116 Hortense	1	450	0	0	0	0	0	0	22
117 Lina	9	45	20	0	78	0	0	0	155
118 Sharon	14	420	20	68	9	1	11	8	94
119 Heather	4	461	1	41	6	0	0	0	41

Table G5: Simplified Octants of Motion for Selected Racetrack Rock Trails, 1996

Rock Number/ Name	Number of Turns	Octants of Motion							
		0 (0° to 45°)	1 (46° to 90°)	2 (91° to 135°)	3 (136° to 180°)	4 (181° to 225°)	5 (226° to 270°)	6 (271° to 315°)	7 (316° to 360°)
120 Fortunata	5	515	10	0	0	0	0	0	22
121 Rose	5	0	0	75	28	49	1	84	0
122 Marlene	4	126	3	0	0	0	0	5	22
123 Amanda	21	202	0	0	0	0	21	194	234
124 Rachel	0	31	0	0	0	0	0	0	0
125 Christine	0	18	0	0	0	0	0	0	11
126 Blanca	8	0	0	0	17	281	108	0	0
127 Mamie	0	0	0	0	0	0	0	0	38
128 Carol	1	2	1	0	17	99	0	0	0
129 Esther	6	10	0	0	0	0	0	9	86
130 Andrea	11	226	8	0	76	4	0	0	179
131 Brianna	15	174	2	0	0	0	0	20	103
132 Goldy	1	231	0	0	0	0	0	0	20
133 Jill	0	58	0	0	0	0	0	0	0
134 Molly	5	12	111	0	0	0	0	0	1
135 Hanna	11	120	22	0	0	0	0	16	75
137 Carmina	11	337	5	1	0	0	0	2	148
138 Florence	14	288	0	0	0	0	0	18	126
139 Agnes	0	0	0	0	0	0	0	1	10
140 Debbie	21	116	0	0	0	0	103	179	209
141 April	13	193	23	2	0	0	0	0	43
142 Cindy	1	91	0	0	0	0	0	0	29
143 Betsy	13	1311	42	0	0	0	0	0	223

Table G5: Simplified Octants of Motion for Selected Racetrack Rock Trails, 1996

Rock Number/ Name	Number of Turns	Octants of Motion							
		0 (0° to 45°)	1 (46° to 90°)	2 (91° to 135°)	3 (136° to 180°)	4 (181° to 225°)	5 (226° to 270°)	6 (271° to 315°)	7 (316° to 360°)
144 Milly	19	1139	32	0	0	4	0	10	134
145 Diane	39	1489	89	0	0	0	0	8	172
146 Dion	21	763	22	0	0	0	0	2	39
147 Kristy	15	1120	135	3	4	0	0	0	48
148 Bonnie	5	214	106	0	0	0	0	0	43
150 Ryan	5	318	55	0	0	0	0	0	41
151 Allison	7	510	114	0	0	0	0	0	61
152 Carmen	7	513	72	0	0	0	0	0	98
153 Layla	9	372	72	0	0	0	0	0	59
154 Marion	9	652	0	0	0	0	0	0	118
155 Aileen	5	798	63	0	0	0	0	0	90
156 Ruth	13	818	6	0	0	0	0	0	51
157 Alanis	13	450	46	0	0	0	0	0	76
158 Sophie	20	595	79	9	0	0	42	58	123
159 June	3	366	41	0	0	0	0	0	0
160 Helen	10	34	32	123	23	19	10	33	19
161 Hillary	9	230	2	113	8	0	0	16	71
162 Tanya	3	798	0	0	0	0	0	0	11

Table G6: Derived Trail Heading Data for Selected Racetrack Rocks, 1996

Rock Number/Name	Percentage of Total Distance Traveled in Each Octant							
	0 (0° to 45°)	1 (46° to 90°)	2 (91° to 135°)	3 (136° to 180°)	4 (181° to 225°)	5 (226° to 270°)	6 (271° to 315°)	7 (316° to 360°)
021 Stacy	0.00%	0.00%	0.00%	0.00%	40.21%	1.03%	6.19%	52.58%
022 Roberta	63.25%	0.18%	0.18%	11.70%	0.91%	2.01%	3.66%	18.10%
023 Violet	86.53%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	13.47%
024 Virginia	85.63%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	14.38%
025 XX	76.30%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	23.70%
026 Johanna	44.11%	8.28%	5.10%	16.40%	1.59%	4.94%	7.80%	11.78%
027 Colette	72.85%	0.20%	0.00%	0.00%	0.00%	0.00%	0.00%	26.95%
028 Danette	67.31%	1.04%	0.59%	12.28%	1.33%	2.07%	6.95%	8.43%
029 Michele	53.49%	0.78%	2.33%	8.53%	1.55%	0.78%	12.40%	20.16%
030 Theresa	68.68%	0.00%	0.00%	0.00%	2.06%	1.92%	0.14%	27.20%
031 Jacki	46.65%	6.02%	7.12%	9.08%	0.68%	1.95%	4.33%	24.17%
032 Amelia	51.01%	4.65%	6.05%	18.32%	0.35%	0.53%	2.19%	16.91%
033 Cynthia	59.55%	3.60%	8.28%	7.74%	0.13%	1.20%	2.80%	16.69%

Table G6: Derived Trail Heading Data for Selected Racetrack Rocks, 1996

Rock Number/Name	Percentage of Total Distance Traveled in Each Octant							
	0 (0° to 45°)	1 (46° to 90°)	2 (91° to 135°)	3 (136° to 180°)	4 (181° to 225°)	5 (226° to 270°)	6 (271° to 315°)	7 (316° to 360°)
034 Pamela	58.40%	2.40%	5.94%	5.83%	0.00%	0.80%	2.17%	24.46%
035 Ev	0.34%	0.34%	3.77%	58.22%	3.77%	10.96%	19.86%	2.74%
036 Jeannine	75.64%	0.00%	0.43%	0.43%	0.00%	0.00%	0.00%	23.50%
037 Mary	83.54%	0.50%	0.00%	0.00%	0.00%	0.00%	0.00%	15.96%
040 Fran	42.76%	0.71%	8.13%	23.32%	0.35%	3.53%	12.37%	8.83%
041 Thelma	89.04%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	10.96%
042 Mona	34.31%	0.00%	0.00%	0.00%	0.00%	24.27%	35.77%	5.65%
043 Joanne	84.31%	4.00%	0.00%	0.00%	0.00%	0.00%	0.00%	11.69%
044 Robin	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	6.90%	93.10%
045 Karen	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.0%
046 Clem	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
047 Peggy	20.00%	80.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
048 Mary- Ann	0.00%	0.00%	0.00%	100.0%	0.00%	0.00%	0.00%	0.00%
049 Edna	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.0%

Table G6: Derived Trail Heading Data for Selected Racetrack Rocks, 1996

Rock Number/Name	Percentage of Total Distance Traveled in Each Octant							
	0 (0° to 45°)	1 (46° to 90°)	2 (91° to 135°)	3 (136° to 180°)	4 (181° to 225°)	5 (226° to 270°)	6 (271° to 315°)	7 (316° to 360°)
050 Alice	27.71%	1.04%	20.42%	31.88%	1.88%	6.25%	8.33%	2.50%
051 Barbara	56.58%	5.69%	4.63%	3.56%	2.49%	4.63%	7.47%	14.95%
052 Jennifer	0.00%	30.19%	20.75%	30.66%	0.47%	5.66%	12.26%	0.00%
053 Shirley	59.65%	2.55%	3.78%	5.63%	0.00%	1.16%	3.70%	23.53%
054 Janet	0.00%	29.07%	16.26%	32.18%	2.08%	1.73%	10.03%	8.65%
055 Julie	52.78%	9.72%	3.87%	6.94%	0.10%	1.29%	6.15%	19.15%
056 Lisa	0.00%	100.0%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
057 Susan	74.70%	0.00%	0.20%	2.59%	0.00%	0.00%	0.00%	22.51%
058 Rhonda	95.09%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	4.91%
059 Irene	75.68%	2.21%	0.00%	0.00%	0.00%	0.00%	0.00%	22.11%
060 Rebecca	60.84%	2.55%	2.38%	3.86%	1.31%	2.30%	5.34%	21.43%
061 Gabby	71.81%	1.49%	0.00%	0.00%	0.00%	1.80%	1.49%	23.41%
062 Clara	75.36%	5.87%	0.27%	0.00%	0.00%	0.00%	1.33%	17.17%
063 Marietta	44.85%	10.29%	0.00%	0.00%	0.00%	0.00%	0.00%	44.85%

Table G6: Derived Trail Heading Data for Selected Racetrack Rocks, 1996

Rock Number/Name	Percentage of Total Distance Traveled in Each Octant							
	0 (0° to 45°)	1 (46° to 90°)	2 (91° to 135°)	3 (136° to 180°)	4 (181° to 225°)	5 (226° to 270°)	6 (271° to 315°)	7 (316° to 360°)
064 Xenio	25.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	75.00%
068 Leslie	0.00%	0.00%	0.00%	55.00%	45.00%	0.00%	0.00%	0.00%
069 Sandra	97.38%	2.62%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
070 Linda	6.33%	0.00%	0.00%	14.25%	6.58%	13.28%	16.08%	43.48%
072 Angel	0.00%	0.36%	0.00%	74.37%	0.36%	18.05%	6.86%	0.00%
073 Claudia	4.61%	0.00%	0.00%	53.87%	4.06%	0.00%	9.23%	28.23%
074 Stefanie	75.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	25.00%
075 Stella	95.00%	5.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
077 Tammy	92.45%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	7.55%
078 Lottie	85.19%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	14.81%
079 Martina	87.68%	0.00%	0.99%	1.48%	0.00%	0.00%	0.00%	9.85%
080 Sheryl	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100%	0.00%
081 Katie	17.49%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	82.51%
082 Nicole	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.0%

Table G6: Derived Trail Heading Data for Selected Racetrack Rocks, 1996

Rock Number/Name	Percentage of Total Distance Traveled in Each Octant							
	0 (0° to 45°)	1 (46° to 90°)	2 (91° to 135°)	3 (136° to 180°)	4 (181° to 225°)	5 (226° to 270°)	6 (271° to 315°)	7 (316° to 360°)
083 Eileen	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.0%
084 Jose- phine	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
085 Matilda	98.32%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.68%
086 Patricia	89.38%	0.88%	1.77%	2.21%	0.66%	0.00%	0.00%	5.09%
087 Nilufer	53.55%	1.09%	1.64%	13.11%	0.00%	0.55%	18.03%	12.02%
088 Sherry	51.68%	0.00%	0.00%	0.00%	2.52%	0.84%	15.97%	28.99%
089 Bep	71.56%	2.86%	0.18%	7.69%	0.00%	0.00%	0.00%	17.71%
090 Glenda	40.17%	2.26%	10.25%	10.37%	0.60%	2.86%	5.72%	27.77%
091 Ellen	3.62%	2.26%	1.96%	13.57%	2.87%	26.09%	42.68%	6.94%
092 Ossie	0.00%	0.00%	78.95%	21.05%	0.00%	0.00%	0.00%	0.00%
093 Bessie	30.72%	24.18%	0.00%	0.00%	0.00%	0.65%	4.58%	39.87%
094 Kitty	0.00%	0.00%	0.00%	0.00%	0.00%	4.76%	78.73%	16.51%
095 Celia	62.53%	2.99%	0.00%	0.00%	0.00%	0.00%	0.00%	34.48%
096 Marie	67.41%	0.00%	0.17%	1.21%	0.69%	0.34%	0.00%	30.17%

Table G6: Derived Trail Heading Data for Selected Racetrack Rocks, 1996

Rock Number/Name	Percentage of Total Distance Traveled in Each Octant							
	0 (0° to 45°)	1 (46° to 90°)	2 (91° to 135°)	3 (136° to 180°)	4 (181° to 225°)	5 (226° to 270°)	6 (271° to 315°)	7 (316° to 360°)
097 Laura	77.10%	0.00%	0.00%	0.55%	2.21%	0.14%	0.14%	19.86%
099 Margot	42.16%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	57.84%
100 Chantal	20.97%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	79.03%
101 Eliza- beth	25.64%	74.36%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
102 Anne	39.67%	0.55%	3.86%	0.00%	0.00%	0.00%	0.00%	55.92%
103 Caroline	23.94%	3.19%	0.00%	21.28%	1.06%	0.00%	1.06%	49.47%
104 Betty	78.82%	0.27%	0.27%	0.00%	0.00%	0.00%	0.00%	20.64%
105 Wilma	83.13%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	16.87%
106 Dottie	76.20%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	23.80%
107 Trish	12.57%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	87.43%
108 Rolanda	55.43%	36.00%	8.00%	0.57%	0.00%	0.00%	0.00%	0.00%
109 Marga- ret	38.95%	16.84%	10.53%	0.00%	0.00%	0.00%	0.70%	32.98%
110 Sara	33.99%	21.67%	0.00%	0.00%	0.00%	0.00%	0.00%	44.33%

Table G6: Derived Trail Heading Data for Selected Racetrack Rocks, 1996

Rock Number/Name	Percentage of Total Distance Traveled in Each Octant							
	0 (0° to 45°)	1 (46° to 90°)	2 (91° to 135°)	3 (136° to 180°)	4 (181° to 225°)	5 (226° to 270°)	6 (271° to 315°)	7 (316° to 360°)
111 Martha	55.88%	25.49%	0.00%	0.00%	0.00%	0.00%	0.00%	18.63%
112 Rose- marie	60.64%	1.06%	23.40%	0.00%	0.00%	0.00%	0.00%	14.89%
113 Sylvia	87.39%	0.00%	0.00%	0.00%	0.00%	0.00%	0.87%	11.74%
114 Minnie	77.41%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	22.59%
115 Denise	75.17%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	24.83%
116 Hortense	95.34%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	4.66%
117 Lina	15.10%	6.71%	0.00%	26.17%	0.00%	0.00%	0.00%	52.01%
118 Sharon	66.56%	3.17%	10.78%	1.43%	0.16%	1.74%	1.27%	14.90%
119 Heather	83.82%	0.18%	7.45%	1.09%	0.00%	0.00%	0.00%	7.45%
120 Fortu- nata	94.15%	1.83%	0.00%	0.00%	0.00%	0.00%	0.00%	4.02%
121 Rose	0.00%	0.00%	31.65%	11.81%	20.68%	0.42%	35.44%	0.00%
122 Marlene	80.77%	1.92%	0.00%	0.00%	0.00%	0.00%	3.21%	14.10%
123 Amanda	31.03%	0.00%	0.00%	0.00%	0.00%	3.23%	29.80%	35.94%

Table G6: Derived Trail Heading Data for Selected Racetrack Rocks, 1996

Rock Number/Name	Percentage of Total Distance Traveled in Each Octant							
	0 (0° to 45°)	1 (46° to 90°)	2 (91° to 135°)	3 (136° to 180°)	4 (181° to 225°)	5 (226° to 270°)	6 (271° to 315°)	7 (316° to 360°)
124 Rachel	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
125 Chris- tine	62.07%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	37.93%
126 Blanca	0.00%	0.00%	0.00%	4.19%	69.21%	26.60%	0.00%	0.00%
127 Mamie	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.0%
128 Carol	1.68%	0.84%	0.00%	14.29%	83.19%	0.00%	0.00%	0.00%
129 Esther	9.52%	0.00%	0.00%	0.00%	0.00%	0.00%	8.57%	81.90%
130 Andrea	45.84%	1.62%	0.00%	15.42%	0.81%	0.00%	0.00%	36.31%
131 Brianna	58.19%	0.67%	0.00%	0.00%	0.00%	0.00%	6.69%	34.45%
132 Goldy	92.03%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	7.97%
133 Jill	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
134 Molly	9.68%	89.52%	0.00%	0.00%	0.00%	0.00%	0.00%	0.81%
135 Hanna	51.50%	9.44%	0.00%	0.00%	0.00%	0.00%	6.87%	32.19%
137 Carmina	68.36%	1.01%	0.20%	0.00%	0.00%	0.00%	0.41%	30.02%
138 Florence	66.67%	0.00%	0.00%	0.00%	0.00%	0.00%	4.17%	29.17%

Table G6: Derived Trail Heading Data for Selected Racetrack Rocks, 1996

Rock Number/Name	Percentage of Total Distance Traveled in Each Octant							
	0 (0° to 45°)	1 (46° to 90°)	2 (91° to 135°)	3 (136° to 180°)	4 (181° to 225°)	5 (226° to 270°)	6 (271° to 315°)	7 (316° to 360°)
139 Agnes	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	9.09%	90.91%
140 Debbie	19.11%	0.00%	0.00%	0.00%	0.00%	16.97%	29.49%	34.43%
141 April	73.95%	8.81%	0.77%	0.00%	0.00%	0.00%	0.00%	16.48%
142 Cindy	75.83%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	24.17%
143 Betsy	83.19%	2.66%	0.00%	0.00%	0.00%	0.00%	0.00%	14.15%
144 Milly	86.35%	2.43%	0.00%	0.00%	0.30%	0.00%	0.76%	10.16%
145 Diane	84.70%	5.06%	0.00%	0.00%	0.00%	0.00%	0.46%	9.78%
146 Dion	92.37%	2.66%	0.00%	0.00%	0.00%	0.00%	0.24%	4.72%
147 Kristy	85.50%	10.31%	0.23%	0.31%	0.00%	0.00%	0.00%	3.66%
148 Bonnie	58.95%	29.20%	0.00%	0.00%	0.00%	0.00%	0.00%	11.85%
150 Ryan	76.81%	13.29%	0.00%	0.00%	0.00%	0.00%	0.00%	9.90%
151 Allison	74.45%	16.64%	0.00%	0.00%	0.00%	0.00%	0.00%	8.91%
152 Carmen	75.11%	10.54%	0.00%	0.00%	0.00%	0.00%	0.00%	14.35%
153 Layla	73.96%	14.31%	0.00%	0.00%	0.00%	0.00%	0.00%	11.73%

Table G6: Derived Trail Heading Data for Selected Racetrack Rocks, 1996

Rock Number/Name	Percentage of Total Distance Traveled in Each Octant							
	0 (0° to 45°)	1 (46° to 90°)	2 (91° to 135°)	3 (136° to 180°)	4 (181° to 225°)	5 (226° to 270°)	6 (271° to 315°)	7 (316° to 360°)
154 Marion	84.68%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	15.32%
155 Aileen	83.91%	6.62%	0.00%	0.00%	0.00%	0.00%	0.00%	9.46%
156 Ruth	93.49%	0.69%	0.00%	0.00%	0.00%	0.00%	0.00%	5.83%
157 Alanis	78.67%	8.04%	0.00%	0.00%	0.00%	0.00%	0.00%	13.29%
158 Sophie	65.67%	8.72%	0.99%	0.00%	0.00%	4.64%	6.40%	13.58%
159 June	89.93%	10.07%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
160 Helen	11.60%	10.92%	41.98%	7.85%	6.48%	3.41%	11.26%	6.48%
161 Hillary	52.27%	0.45%	25.68%	1.82%	0.00%	0.00%	3.64%	16.14%
162 Tanya	98.64%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.36%

Table G7: Location of Trail Start and End Points Relative to Hydrologic Features

Rock Number/ Name	Trail Start Point		Trail End Point		Straight line Distance from Springs (start)	Straight line Distance from Springs (end)
	East- West Distance to Spring (X)	North- South Distance to Spring (Y)	East- West Distance to Spring (X)	North- South Distance to Spring (Y)		
021 Stacy	955.19	1112.59	974.33	1102.75	1466.37	1471.53
022 Roberta	1052.67	1282.85	988.14	1109.50	1659.47	1485.73
023 Violet	1040.30	1145.67	1007.29	1029.24	1547.51	1440.13
024 Virginia	1028.34	1105.42	1007.21	1029.37	1509.78	1440.16
025 XX	1029.64	1102.57	965.18	889.77	1508.58	1312.73
026 Johanna	1019.96	1027.42	949.62	915.29	1447.72	1318.91
027 Colette	1015.78	1112.27	949.68	875.29	1506.30	1291.52
028 Danette	957.54	972.44	876.43	769.96	1364.74	1166.60
029 Michele	842.35	756.33	837.30	714.33	1132.08	1100.61
030 Theresa	881.20	1053.83	820.07	733.57	1373.71	1100.29
031 Jacki	876.01	1088.47	751.93	753.86	1397.20	1064.76
032 Amelia	907.09	1106.71	734.55	836.03	1430.95	1112.89
033 Cynthia	832.10	1063.04	731.91	825.67	1349.98	1103.37
034 Pamela	885.11	1130.75	770.61	822.10	1435.98	1126.81
035 Ev	830.17	826.98	821.41	894.85	1171.78	1214.69
036 Jeannine	850.39	1026.54	823.68	919.69	1333.02	1234.62
037 Mary	908.93	1108.88	846.48	924.85	1433.80	1253.74
040 Fran	964.52	992.81	933.03	952.21	1384.19	1333.14
041 Thelma	958.59	1066.27	924.87	963.46	1433.82	1335.53
042 Mona	793.92	1072.69	905.12	967.81	1334.53	1325.10
043 Joanne	978.41	968.06	920.51	820.03	1376.38	1232.80
044 Robin	922.63	731.14	967.54	611.24	1177.20	1144.45

Table G7: Location of Trail Start and End Points Relative to Hydrologic Features

Rock Number/ Name	Trail Start Point		Trail End Point		Straight line Distance from Springs (start)	Straight line Distance from Springs (end)
	East- West Distance to Spring (X)	North- South Distance to Spring (Y)	East- West Distance to Spring (X)	North- South Distance to Spring (Y)		
045 Karen	981.58	423.59	985.46	405.22	1069.07	1065.52
046 Clem	1176.86	435.77	1135.48	377.86	1254.95	1196.70
047 Peggy	1145.16	530.60	1097.38	491.12	1262.12	1202.26
048 MaryAnn	930.11	508.52	929.54	509.81	1060.04	1060.17
049 Edna	931.83	518.40	933.81	515.16	1066.32	1066.49
050 Alice	771.96	612.49	710.71	636.30	985.43	953.93
051 Barbara	738.75	732.35	727.01	639.99	1040.24	968.57
052 Jennifer	760.60	626.86	710.99	653.06	985.63	965.40
053 Shirley	840.28	1168.54	694.23	688.06	1439.29	977.44
054 Janet	768.96	670.32	711.02	694.53	1020.11	993.94
055 Julie	882.55	1090.24	758.38	758.89	1402.68	1072.87
056 Lisa	755.06	766.31	752.29	765.61	1075.80	1073.36
057 Susan	898.23	1407.11	831.93	1194.26	1669.37	1455.46
058 Rhonda	826.95	1184.11	796.51	1108.99	1444.28	1365.38
059 Irene	785.01	1129.17	692.85	774.39	1375.24	1039.10
060 Rebecca	784.05	1037.84	689.93	581.53	1300.71	902.31
061 Gabby	780.84	1134.22	663.03	558.63	1377.02	867.00
062 Clara	807.92	1189.35	678.26	675.97	1437.81	957.59
063 Marietta	791.09	1343.43	783.46	1285.71	1559.04	1505.61
064 Xenio	808.65	1189.04	808.62	1180.40	1437.97	1430.81
068 Leslie	840.95	1166.54	840.57	1186.57	1438.06	1454.14
069 Sandra	993.11	1437.08	874.16	1220.93	1746.84	1501.61
070 Linda	730.03	1298.17	870.62	1165.32	1489.36	1454.63

Table G7: Location of Trail Start and End Points Relative to Hydrologic Features

Rock Number/ Name	Trail Start Point		Trail End Point		Straight line Distance from Springs (start)	Straight line Distance from Springs (end)
	East- West Distance to Spring (X)	North- South Distance to Spring (Y)	East- West Distance to Spring (X)	North- South Distance to Spring (Y)		
072 Angel	890.07	1044.77	895.96	1150.54	1372.51	1458.25
073 Claudia	881.88	1020.96	885.23	1071.62	1349.10	1389.96
074 Stefanie	876.84	1099.63	875.63	1087.04	1406.43	1395.85
075 Stella	876.16	1086.29	872.61	1076.06	1395.60	1385.41
077 Tammy	830.31	1269.84	760.18	1102.03	1517.20	1338.79
078 Lottie	794.78	1076.85	781.29	1025.09	1338.39	1288.89
079 Martina	811.61	1117.15	781.01	1025.96	1380.85	1289.41
080 Sheryl	807.37	1064.22	832.91	1058.37	1335.82	1346.81
081 Katie	728.36	1284.98	748.04	1197.47	1477.05	1411.91
082 Nicole	743.98	1205.55	744.32	1204.02	1416.64	1415.52
083 Eileen	719.52	1297.72	733.84	1254.03	1483.84	1452.97
084 Josephine	769.51	1279.03	735.14	1202.72	1492.67	1409.60
085 Matilda	769.98	1290.25	733.79	1208.30	1502.54	1413.66
086 Patricia	829.98	1270.42	739.83	1083.79	1517.51	1312.23
087 Nilufer	746.70	1046.04	739.29	992.36	1285.21	1237.47
088 Sherry	746.31	1043.60	762.36	946.14	1283.00	1215.06
089 Bep	801.68	1157.52	728.28	942.17	1408.03	1190.83
090 Glenda	865.17	1107.41	786.31	888.89	1405.30	1186.76
091 Ellen	466.59	949.47	669.97	960.79	1057.93	1171.32
092 Ossie	669.66	961.00	661.42	966.57	1171.31	1171.21
093 Bessie	670.80	1024.95	665.00	962.08	1224.95	1169.54
094 Kitty	500.97	1003.05	634.44	938.24	1121.20	1132.61
095 Celia	663.09	1115.59	652.34	909.99	1297.78	1119.65

Table G7: Location of Trail Start and End Points Relative to Hydrologic Features

Rock Number/ Name	Trail Start Point		Trail End Point		Straight line Distance from Springs (start)	Straight line Distance from Springs (end)
	East- West Distance to Spring (X)	North- South Distance to Spring (Y)	East- West Distance to Spring (X)	North- South Distance to Spring (Y)		
096 Marie	744.28	1254.25	689.97	1004.13	1458.46	1218.33
097 Laura	770.94	1313.26	691.26	1004.29	1522.83	1219.19
099 Margot	681.72	1167.29	696.01	1081.09	1351.78	1285.76
100 Chantal	674.38	1150.26	692.91	1092.67	1333.37	1293.85
101 Elizabeth	714.00	1114.50	698.94	1101.65	1323.60	1304.67
102 Anne	703.07	1267.26	710.52	1109.25	1449.23	1317.30
103 Caroline	684.80	1170.15	683.47	1123.01	1355.81	1314.64
104 Betty	726.55	1301.89	681.36	1133.49	1490.90	1322.52
105 Wilma	729.62	1300.44	688.34	1148.91	1491.13	1339.33
106 Dottie	735.22	1305.88	700.81	1145.29	1498.63	1342.70
107 Trish	666.37	1293.87	689.09	1201.93	1455.39	1385.45
108 Rolanda	725.27	1272.94	669.75	1216.02	1465.06	1388.26
109 Margaret	702.26	1322.49	661.36	1218.15	1497.38	1386.11
110 Sara	710.80	1318.32	690.68	1234.89	1497.73	1414.92
111 Martha	723.43	1312.25	704.35	1272.40	1498.45	1454.34
112 Rosemarie	717.27	1311.99	698.41	1281.33	1495.26	1459.31
113 Sylvia	624.47	1342.62	593.76	1236.36	1480.74	1371.55
114 Minnie	694.09	1312.69	650.00	1094.45	1484.90	1272.92
115 Denise	694.29	1312.34	653.39	1109.95	1484.68	1287.99
116 Hortense	716.87	1289.38	615.53	1080.71	1475.26	1243.71
117 Lina	636.96	1168.75	637.23	1107.46	1331.05	1277.70
118 Sharon	691.17	1316.74	589.65	1102.77	1487.12	1250.52
119 Heather	710.16	1296.26	589.65	1090.30	1478.05	1239.53

Table G7: Location of Trail Start and End Points Relative to Hydrologic Features

Rock Number/ Name	Trail Start Point		Trail End Point		Straight line Distance from Springs (start)	Straight line Distance from Springs (end)
	East- West Distance to Spring (X)	North- South Distance to Spring (Y)	East- West Distance to Spring (X)	North- South Distance to Spring (Y)		
120 Fortunata	684.17	1315.41	562.40	1075.85	1482.70	1213.98
121 Rose	556.96	1046.73	563.24	1091.21	1185.68	1228.00
122 Marlene	573.36	1141.40	555.79	1071.65	1277.31	1207.20
123 Amanda	427.15	1257.19	530.18	1015.77	1327.77	1145.81
124 Rachel	428.06	1219.35	422.66	1203.96	1292.31	1275.99
125 Christine	423.31	1217.80	422.98	1203.36	1289.27	1275.54
126 Blanca	329.05	1040.59	425.04	1210.71	1091.38	1283.15
127 Mamie	425.89	1239.80	431.31	1220.72	1310.91	1294.67
128 Carol	423.88	1074.33	434.15	1128.16	1154.92	1208.82
129 Esther	391.20	1148.01	411.54	1102.10	1212.84	1176.43
130 Andrea	412.82	1230.05	381.48	1080.82	1297.48	1146.16
131 Brianna	381.35	1238.77	380.21	1101.15	1296.14	1164.95
132 Goldy	400.15	1214.08	361.35	1096.26	1278.32	1154.28
133 Jill	369.12	1123.59	355.57	1098.04	1182.66	1154.18
134 Molly	377.13	1080.67	331.09	1040.08	1144.59	1091.51
135 Hanna	342.38	1145.08	340.43	1042.38	1195.17	1096.56
137 Carmina	384.15	1227.77	366.75	999.83	1286.46	1064.97
138 Florence	382.26	1208.79	368.87	1007.66	1267.79	1073.05
139 Agnes	396.66	995.98	400.61	991.47	1072.07	1069.34
140 Debbie	280.20	1057.77	417.33	886.69	1094.26	979.98
141 April	53.71	196.14	21.84	78.75	203.36	81.72
142 Cindy	186.20	256.81	184.77	197.86	317.21	270.72
143 Betsy	458.33	982.15	250.95	245.82	1083.83	351.28

Table G7: Location of Trail Start and End Points Relative to Hydrologic Features

Rock Number/ Name	Trail Start Point		Trail End Point		Straight line Distance from Springs (start)	Straight line Distance from Springs (end)
	East- West Distance to Spring (X)	North- South Distance to Spring (Y)	East- West Distance to Spring (X)	North- South Distance to Spring (Y)		
144 Milly	397.17	791.00	223.67	181.38	885.11	287.98
145 Diane	562.49	1105.36	313.35	300.54	1240.25	434.18
146 Dion	459.37	765.93	342.94	378.29	893.13	510.60
147 Kristy	562.80	994.46	328.55	408.01	1142.67	523.85
148 Bonnie	424.98	611.52	355.66	455.52	744.69	577.92
150 Ryan	379.98	691.25	311.01	506.45	788.80	594.32
151 Allison	503.79	800.29	400.42	488.65	945.66	631.75
152 Carmen	522.67	856.35	435.35	539.17	1003.26	692.99
153 Layla	558.83	735.65	489.92	504.04	923.84	702.90
154 Marion	586.07	905.79	505.42	537.97	1078.86	738.15
155A ileen	631.33	1055.53	475.63	626.30	1229.93	786.43
156 Ruth	576.03	1048.02	435.87	642.88	1195.89	776.71
157 Alanis	545.66	950.45	435.93	700.14	1095.95	824.76
158 Sophie	496.32	1067.61	400.35	711.94	1177.34	816.79
159 June	533.49	936.46	439.19	759.92	1077.76	877.71
160 Helen	541.65	780.41	486.53	783.78	949.96	922.51
161 Hillary	563.82	1033.15	490.78	917.37	1176.98	1040.40
162 Tanya	685.75	1275.95	496.09	922.85	1448.56	1047.74

Appendix H: Geomorphometry

Table H1: Sum of Pixel Aspects Visible to Selected Rock Start Points, by Quadrant

Rock Name/Number	N (7 + 0)	E (1 + 2)	S (3 + 4)	W (5 + 6)	NE (0 + 1)	SE (2 + 3)	SW (4 + 5)	NW (6 + 7)
Alice 050	2126	3698	839	3137	2943	1936	2077	2844
Amelia 032	1671	3656	828	3035	2771	1935	2128	2356
April 141	1630	3771	681	2069	2901	1916	1313	2021
Claudia 073	1781	3663	828	3045	2799	1936	2119	2463
Debbie 140	2341	3578	975	4081	2987	1843	2560	3585
Diane 145	1330	3685	748	2449	2703	1919	1704	1886
Jacki 031	1655	3656	819	2985	2776	1931	2106	2302
Josephine 084	955	3625	783	2327	2546	1914	1830	1400
Karen 045	2260	3616	887	3648	2963	1847	2316	3285
Marietta 063	540	3528	754	1927	2351	1858	1643	897
Sandra 069	870	3451	786	2089	2411	1854	1839	1092
Sheryl 080	1636	3656	813	2841	2769	1932	2007	2238

Table H2: Number of Pixel Aspects Visible to Selected Rock Start Points

Rock Name/ Number	N-S	E-W	NE-SW	NW-SE
Alice 050	2965	6835	5020	4780
Amelia 032	2499	6691	4899	4291
April 141	2311	5840	4214	3937
Claudia 073	2609	6708	4918	4399
Debbie 140	3316	7659	5547	5428
Diane 145	2078	6134	4407	3805
Jacki 031	2474	6641	4882	4233

Table H2: Number of Pixel Aspects Visible to Selected Rock Start Points

Rock Name/ Number	N-S	E-W	NE-SW	NW-SE
Josephine 084	1738	5952	4376	3314
Karen 045	3147	7264	5279	5132
Marietta 063	1294	5455	3994	2755
Sandra 069	1656	5540	4250	2946
Sheryl 080	2449	6497	4776	4170

Table H3: Aspect Percentages of Pixels in Selected Rock Viewsheds, by Octant

Rock Name/ Number	Octant							
	0	1	2	3	4	5	6	7
Alice 050	8.74%	21.29%	16.45%	3.31%	5.26%	15.94%	16.07%	12.95%
Amelia 032	7.80%	22.35%	17.43%	3.62%	5.39%	17.77%	15.26%	10.38%
April 141	9.15%	26.44%	19.83%	3.68%	4.67%	11.43%	13.95%	10.85%
Claudia 073	7.94%	22.10%	17.22%	3.56%	5.32%	17.42%	15.26%	11.17%
Debbie 140	8.18%	19.03%	13.57%	3.23%	5.66%	17.67%	19.52%	13.15%
Diane 145	7.55%	25.37%	19.51%	3.86%	5.25%	15.50%	14.32%	8.65%
Jacki 031	7.90%	22.56%	17.55%	3.63%	5.35%	17.75%	15.00%	10.26%
Josephine 084	6.63%	26.48%	20.66%	4.23%	5.96%	17.84%	12.42%	5.79%
Karen 045	8.39%	20.07%	14.66%	3.08%	5.44%	16.81%	18.23%	13.32%
Marietta 063	5.38%	29.46%	22.82%	4.71%	6.46%	17.88%	10.67%	2.62%
Sandra 069	6.84%	26.67%	21.29%	4.47%	6.45%	19.11%	9.92%	5.25%
Sheryl 080	7.98%	22.97%	17.90%	3.70%	5.39%	17.05%	14.71%	10.31%
Mean	7.71%	23.73%	18.24%	3.76%	5.55%	16.85%	14.61%	9.56%

Table H4: Aspect Percentages of Pixels in Selected Rock Viewsheds, by Quadrant

Rock Name/ Number	Quadrant							
	%N	%E	%S	%W	%NE	%SE	%SW	%NW
Alice 050	21.69%	37.73%	8.56%	32.01%	30.03	19.76	21.19	29.02
Amelia 032	18.18	39.78	9.01	33.03	30.15	21.06	23.16	25.64
April 141	20.00	46.26	8.35	25.38	35.59	23.51	16.11	24.79
Claudia 073	19.12	39.32	8.89	32.68	30.04	20.78	22.74	26.44
Debbie 140	21.33	32.60	8.88	37.18	27.22	16.79	23.33	32.67
Diane 145	16.20	44.87	9.11	29.82	32.92	23.37	20.75	22.97
Jacki 031	18.16	40.11	8.99	32.75	30.46	21.18	23.10	25.26
Josephine 084	12.42	47.14	10.18	30.26	33.11	24.89	23.80	18.21
Karen 045	21.71	34.73	8.52	35.04	28.46	17.74	22.25	31.55
Marietta 063	8.00	52.27	11.17	28.55	34.83	27.53	24.34	13.29
Sandra 069	12.09	47.96	10.92	29.03	33.50	25.76	25.56	15.18
Sheryl 080	18.29	40.87	9.09	31.76	30.95	21.60	22.43	25.02
Mean	17.26	41.97	9.31	31.46	31.44	22.00	22.40	24.17

Table H5: Viewshed Aspects Versus Trail Headings for Selected Rocks

Rock Name/ Number	Viewshed				Trail			
	NE-SW	NW-SE	N-S	E-W	NE-SW	NW-SE	N-S	E-W
Alice (50)	51.22%	48.78%	30.25%	69.75%	9.21%	90.79%	80.6%	19.4%
Amelia (32)	53.31%	46.69%	27.19%	72.81%	93.24%	6.76%	86.6%	13.4%
April (141)	51.70%	48.30%	28.35%	71.65%	54.55%	45.45%	100%	0.00%
Claudia (73)	52.79%	47.21%	28.00%	71.00%	0.00%	100%	63.9%	36.0%
Debbie (140)	50.54%	49.46%	30.21%	69.79%	0.00%	100%	89.7%	10.3%
Diane (145)	53.67%	46.33%	25.30%	74.70%	83.08%	16.92%	97.4%	2.6%
Jacki (31)	53.56%	46.44%	27.14%	72.86%	88.68%	11.32%	90.8%	9.2%
Josephine (84)	56.91%	43.09%	22.60%	77.40%	100%	0.00%	0.00%	100%
Karen (45)	50.71%	49.29%	30.23%	69.77%	0.00%	100%	100%	0.00%
Marietta (63)	59.18%	40.82%	19.17%	80.83%	95.65%	4.35%	53.5%	46.5%
Sandra (69)	59.06%	40.94%	23.01%	76.99%	100%	0.00%	90.4%	9.6%
Sheryl (80)	53.39%	46.61%	27.38%	72.62%	0.00%	100%	94.5%	5.5%
Mean	53.84%	46.16%	26.57%	73.43%	51.76%	47.97%	79.0%	21.0%

Table H6: Rock Start Point Viewsheds

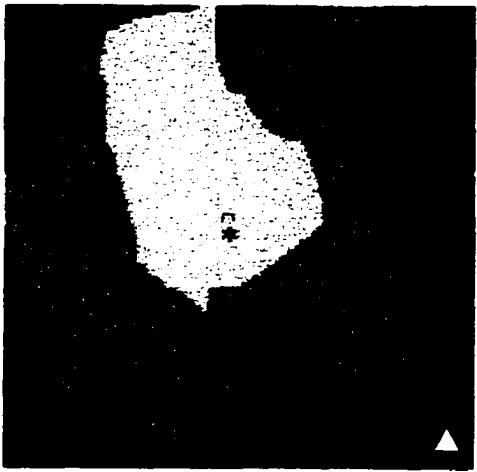
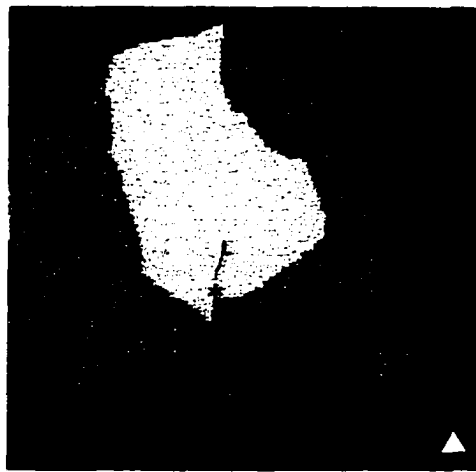
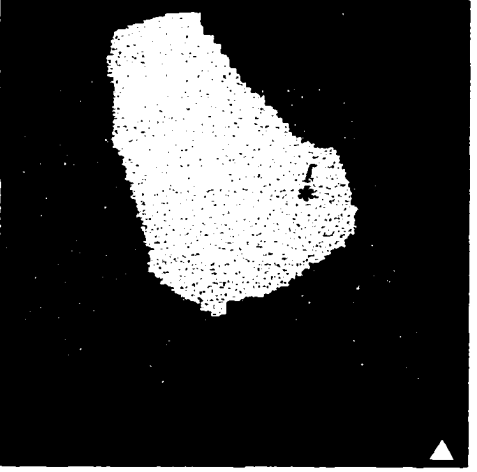
 050 Alice	 032 Amelia
Key: Visible Viewshed  Racetrack Playa  Surrounding Landscape Invisible Terrain Elements  Landscape blocked from view, or beyond 2000-meter buffer ★ Rock location at start of trail └ Trail	
 141 April	 073 Claudia

Table H6: Rock Start Point Viewsheds

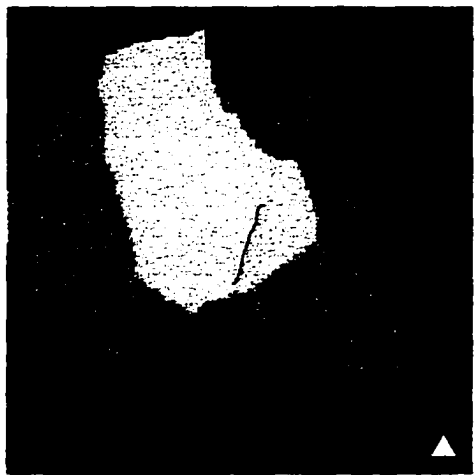
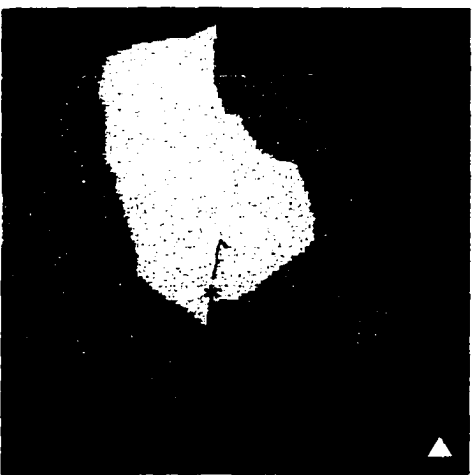
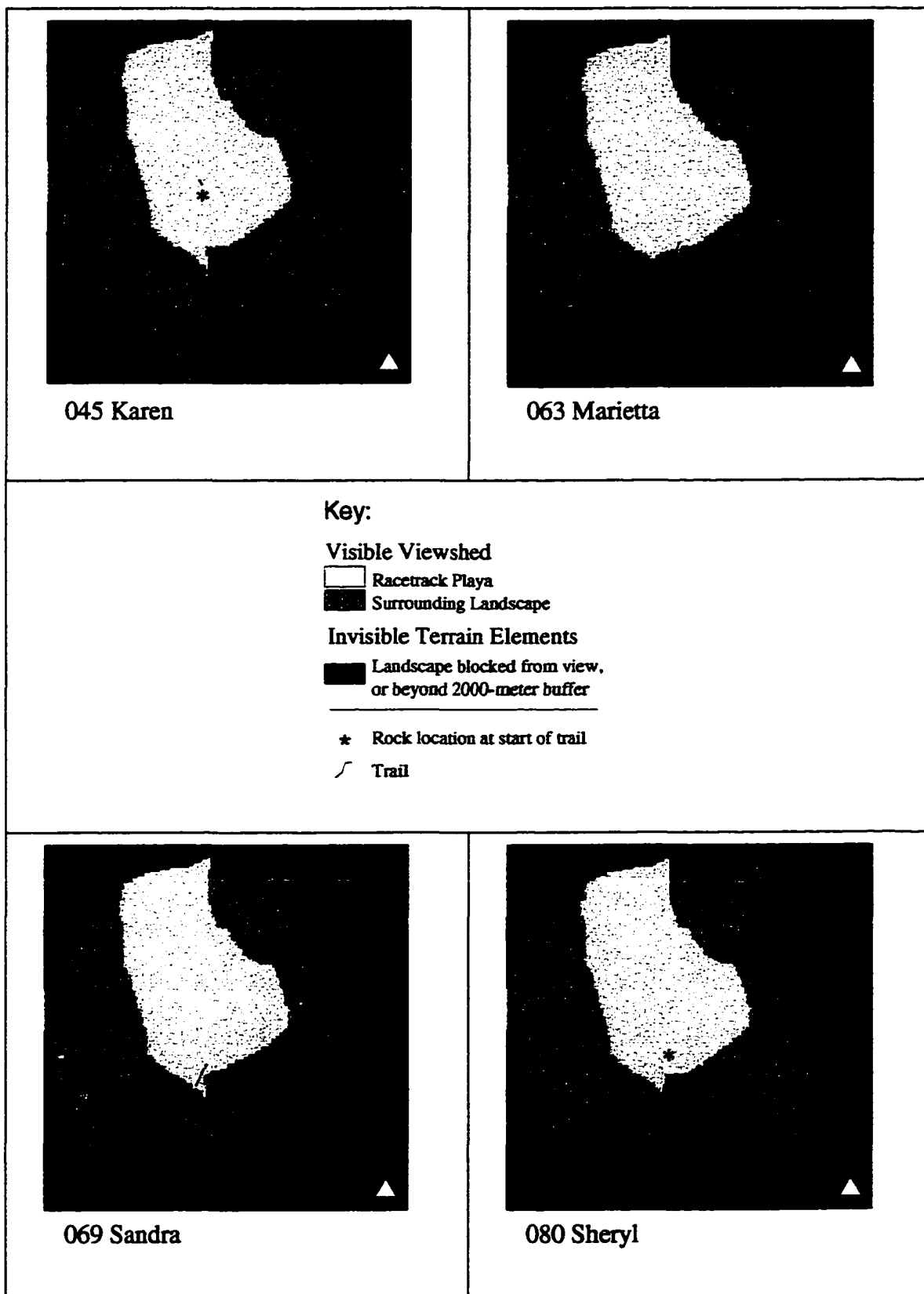
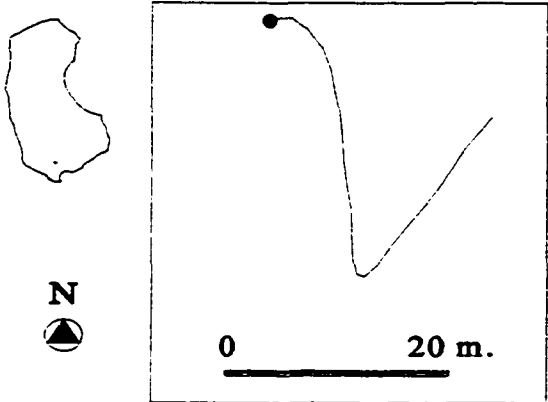
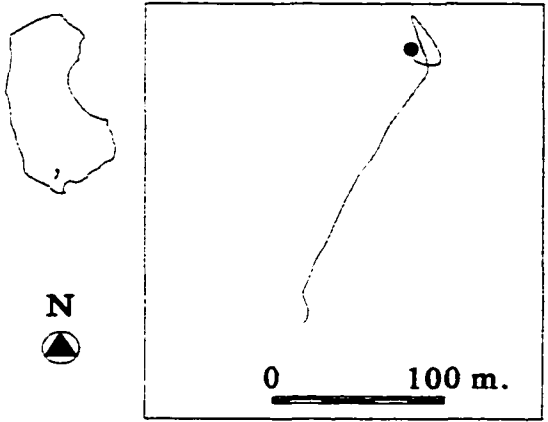
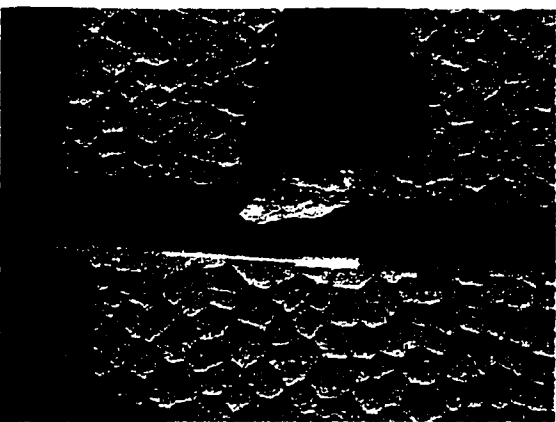
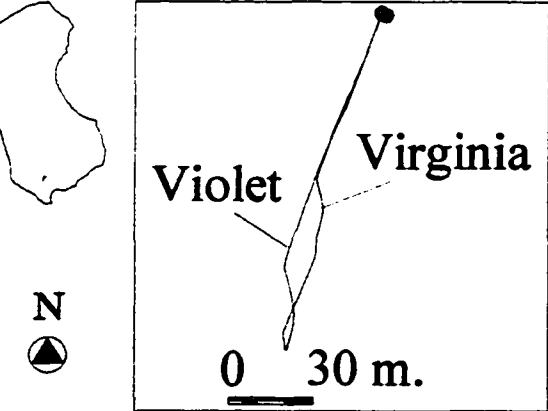
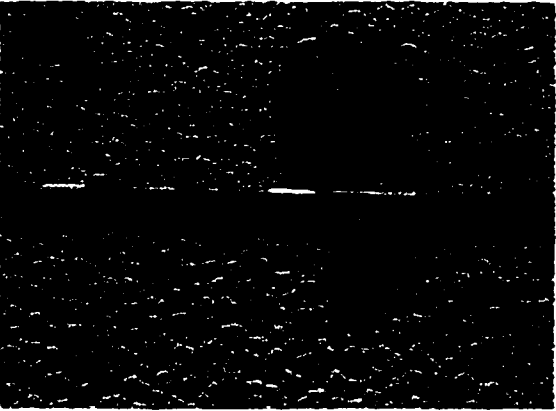
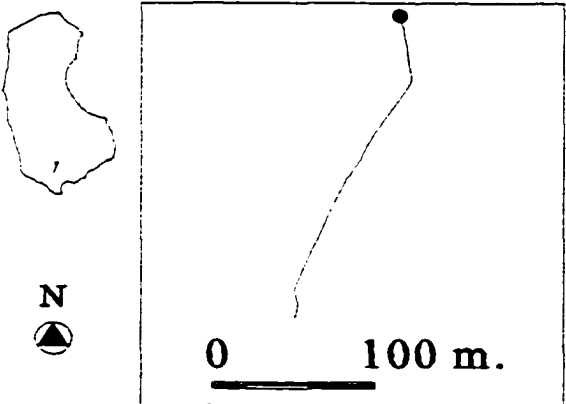
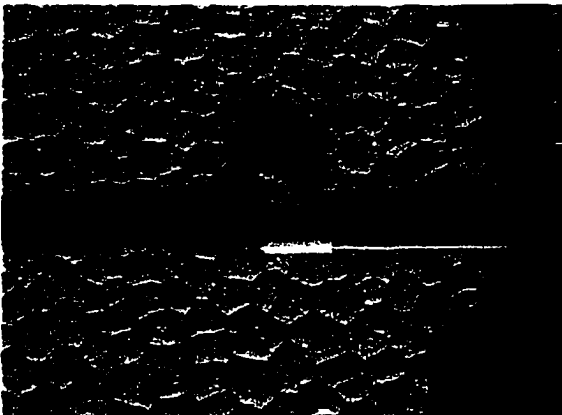
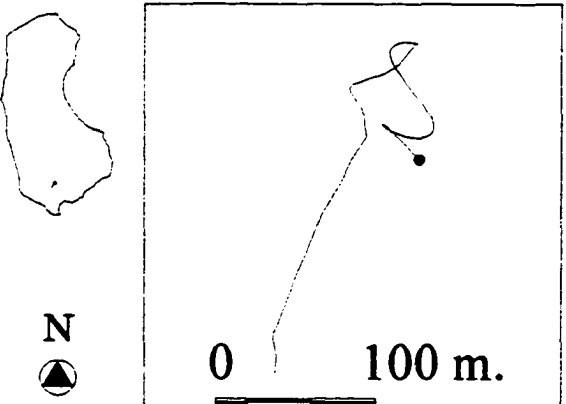
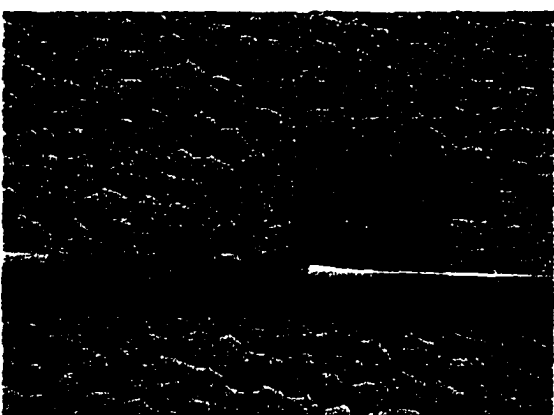
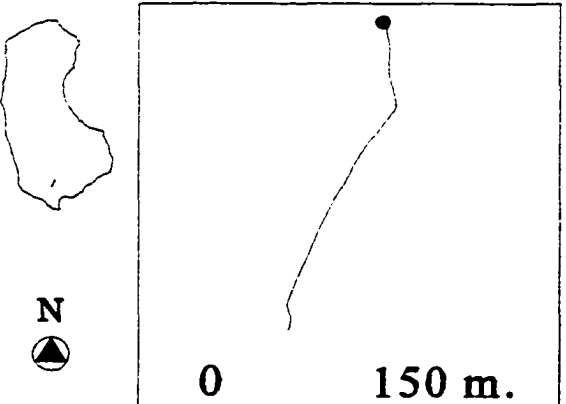
 140 Debbie	 145 Diane
Key: Visible Viewshed  Racetrack Playa  Surrounding Landscape Invisible Terrain Elements  Landscape blocked from view, or beyond 2000-meter buffer ★ Rock location at start of trail ↗ Trail	
 031 Jacki	 084 Josephine

Table H6: Rock Start Point Viewsheds

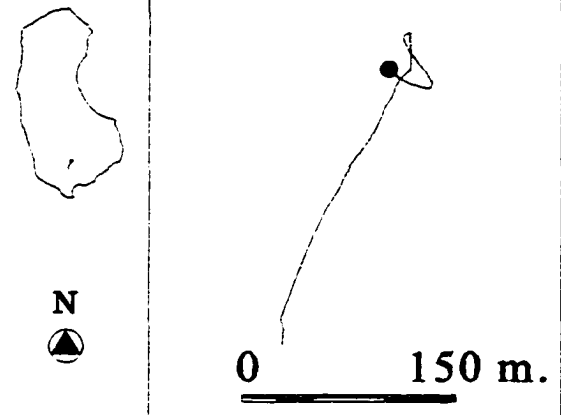
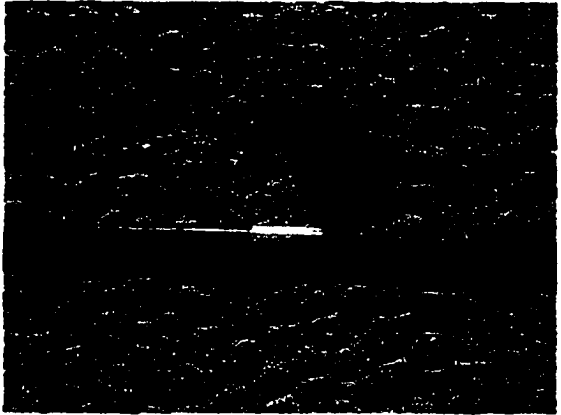
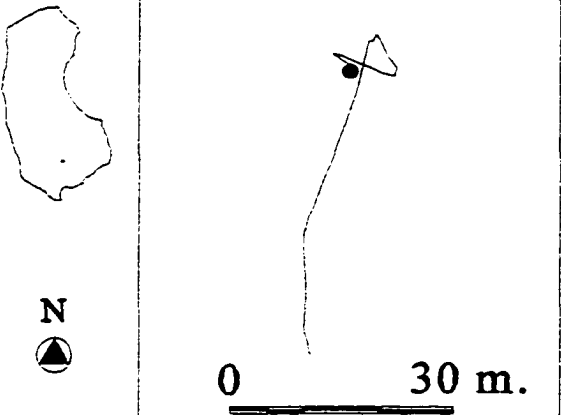
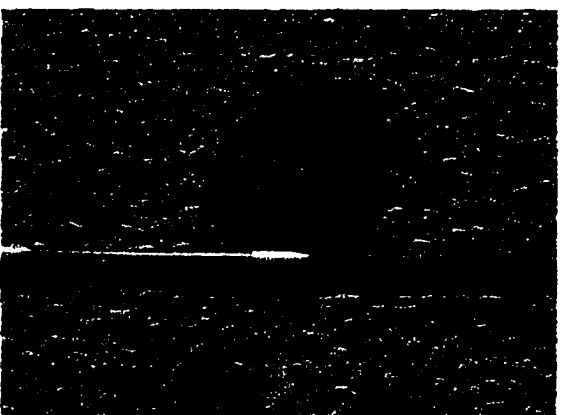
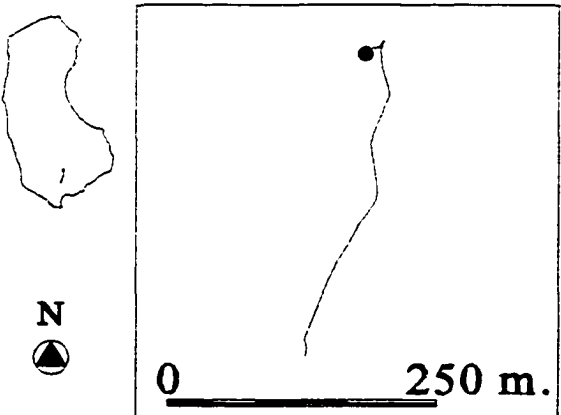
**Appendix I:
Image Database of Sliding Rocks and Trails**

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021 Stacy 	
022 Roberta 	
023 Violet and 024 Virginia 	

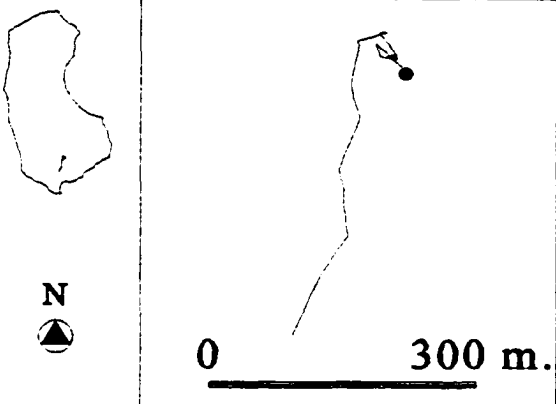
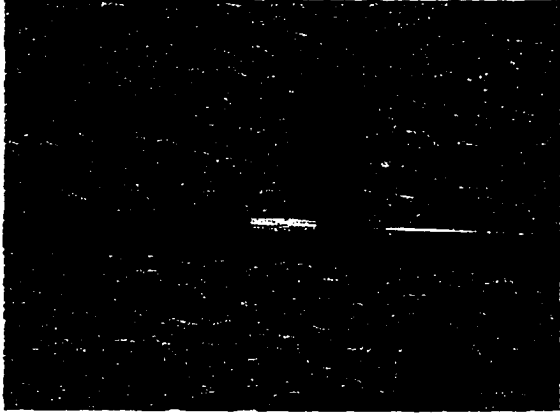
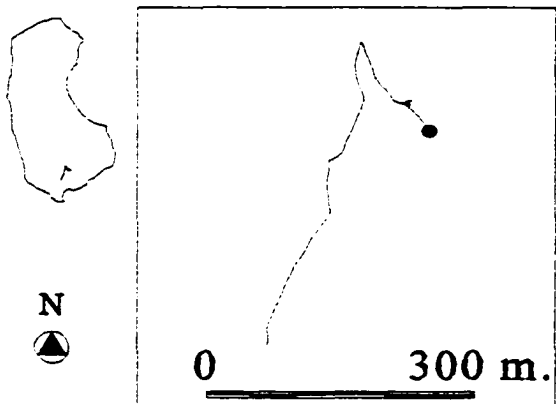
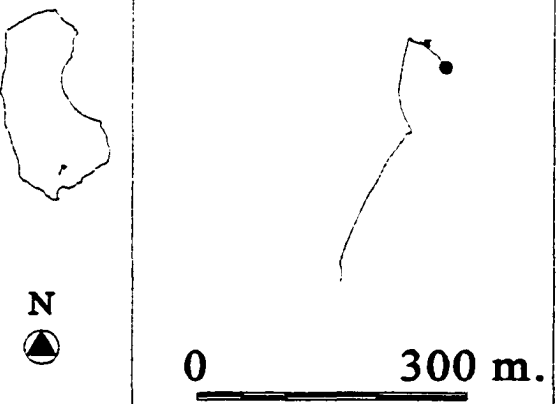
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
025 XX 	
026 Johanna 	
027 Colette 	

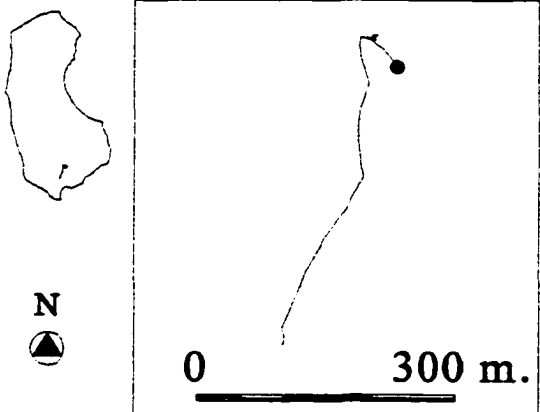
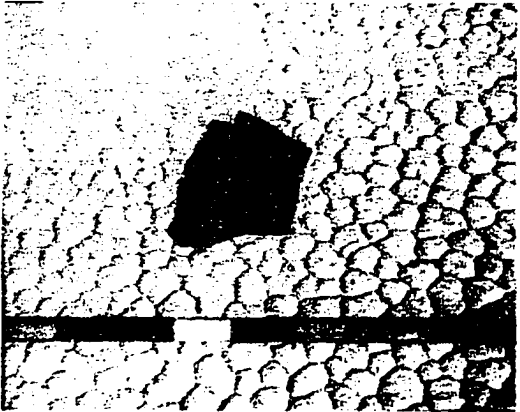
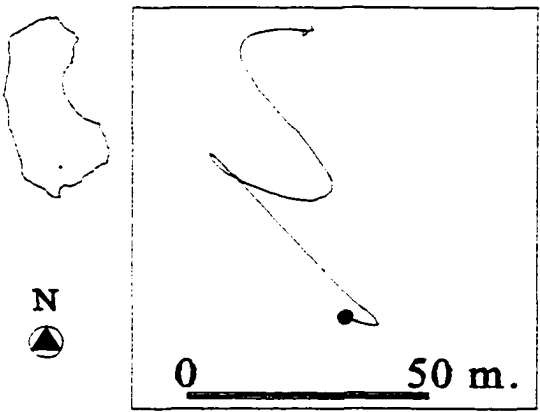
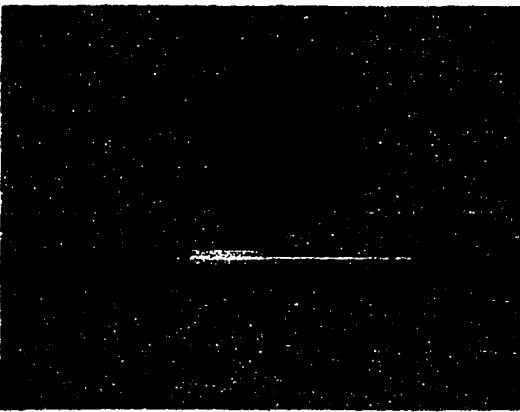
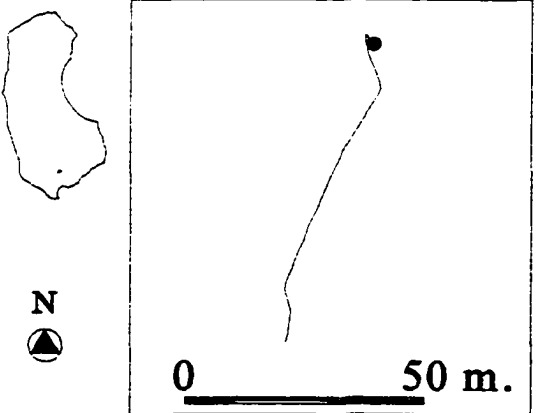
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
028 Danette  The map for site 028 Danette includes a small inset map of the island of Hawaii on the left, with a dot indicating the site's location. The main map shows a trail starting from the bottom and ending at a black dot representing the rock. A north arrow is located at the bottom left, and a scale bar at the bottom indicates 0 to 150 meters.	 A black and white photograph of the rock at site 028 Danette. The rock is a light-colored, elongated object lying on a dark, textured ground. A horizontal white line, representing a 10-centimeter ruler, is placed next to the rock for scale.
029 Michele  The map for site 029 Michele includes a small inset map of the island of Hawaii on the left, with a dot indicating the site's location. The main map shows a trail starting from the bottom and ending at a black dot representing the rock. A north arrow is located at the bottom left, and a scale bar at the bottom indicates 0 to 30 meters.	 A black and white photograph of the rock at site 029 Michele. The rock is a light-colored, elongated object lying on a dark, textured ground. A horizontal white line, representing a 10-centimeter ruler, is placed next to the rock for scale.
030 Theresa  The map for site 030 Theresa includes a small inset map of the island of Hawaii on the left, with a dot indicating the site's location. The main map shows a trail starting from the bottom and ending at a black dot representing the rock. A north arrow is located at the bottom left, and a scale bar at the bottom indicates 0 to 250 meters.	 A black and white photograph of the rock at site 030 Theresa. The rock is a light-colored, elongated object lying on a dark, textured ground. A horizontal white line, representing a 10-centimeter ruler, is placed next to the rock for scale.

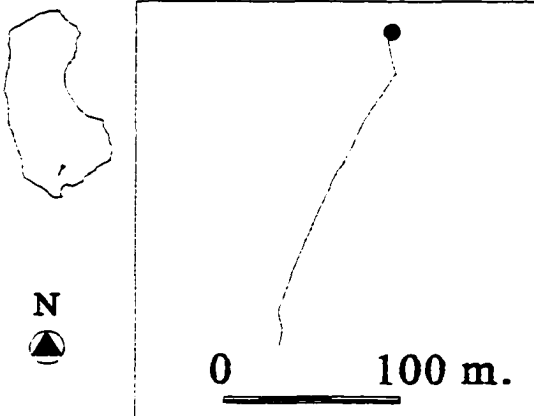
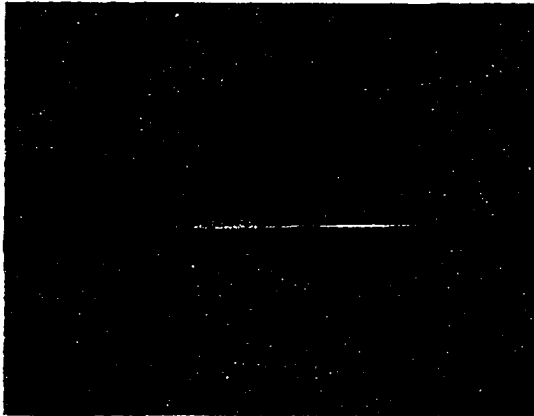
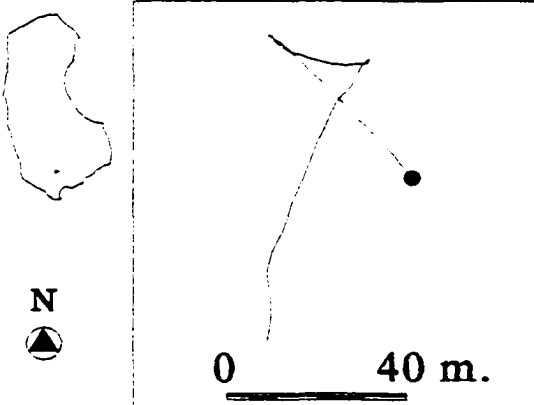
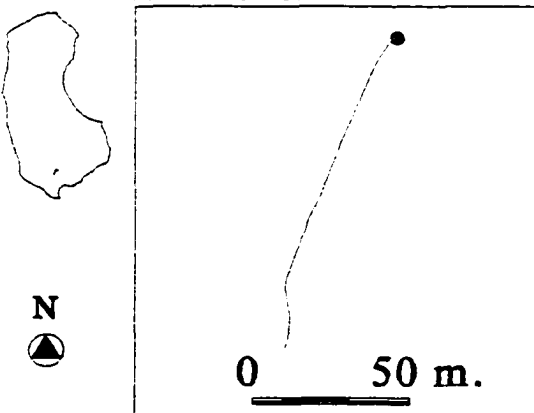
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
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032 Amelia 	
033 Cynthia 	

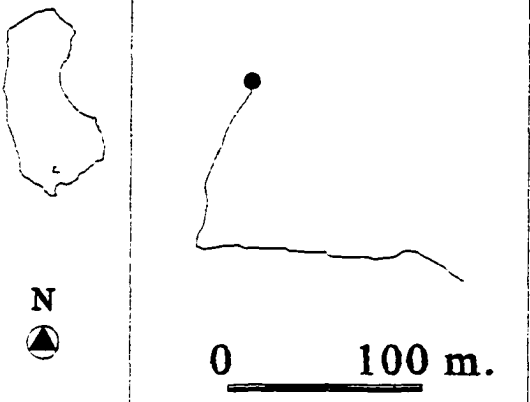
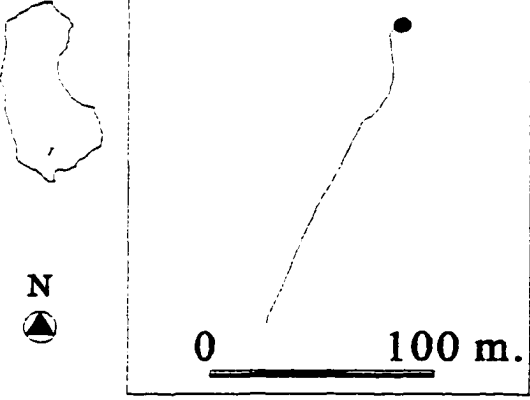
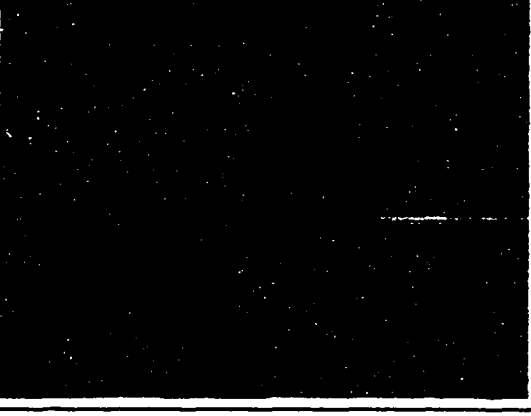
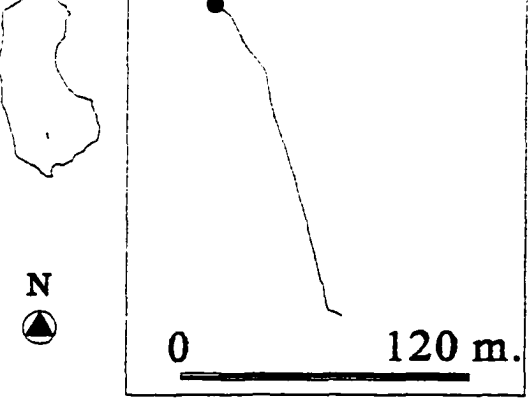
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
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035 Ev 	
036 Jeannine 	

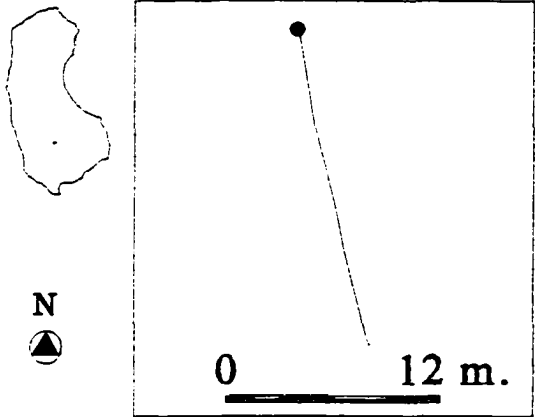
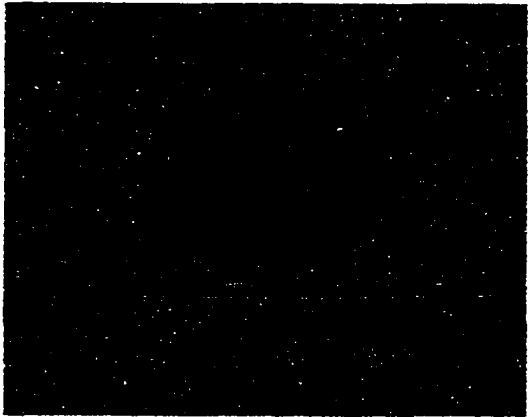
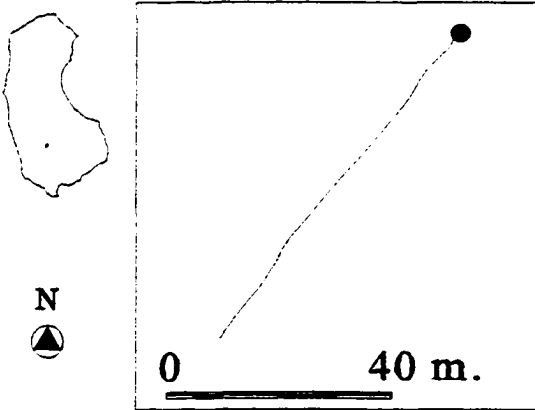
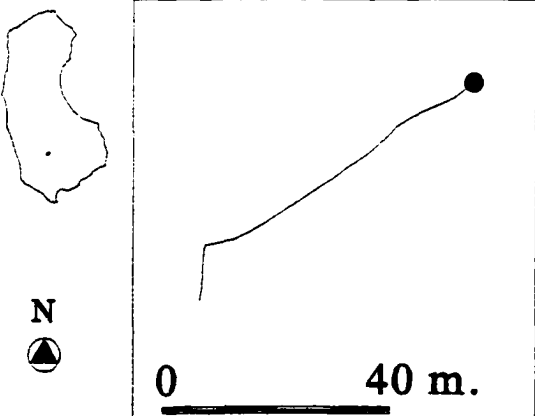
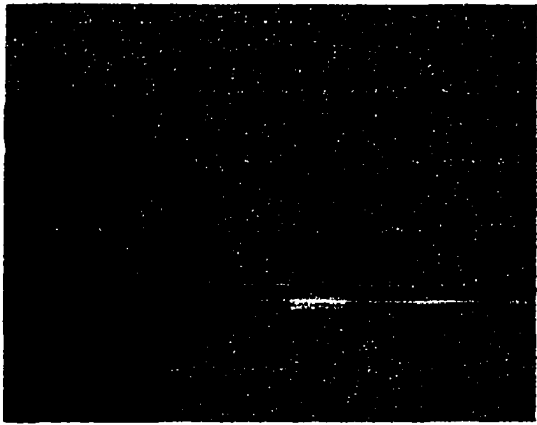
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
037 Mary 	
040 Fran 	
041a Thelma / 041b Louise 	

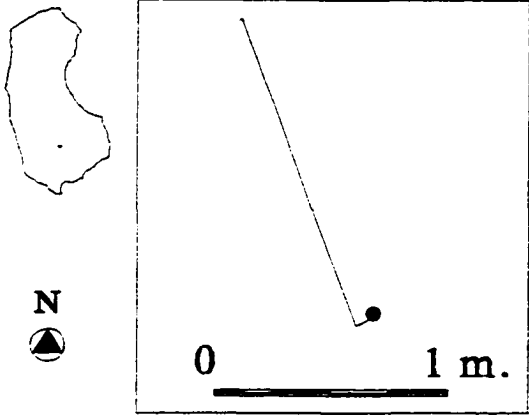
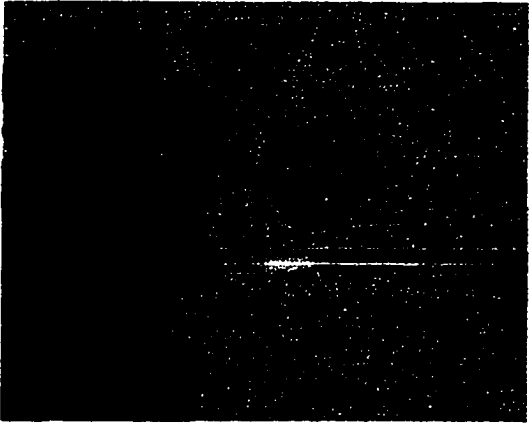
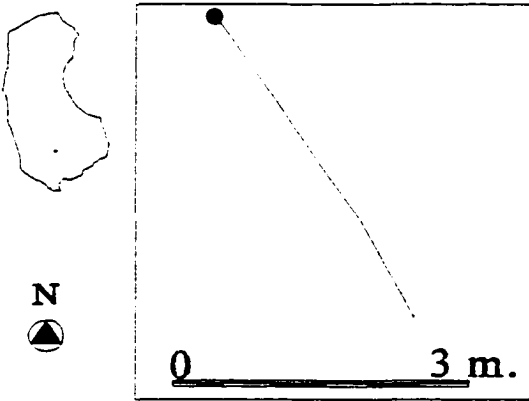
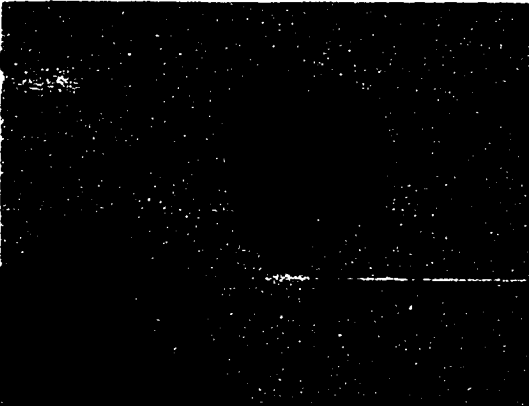
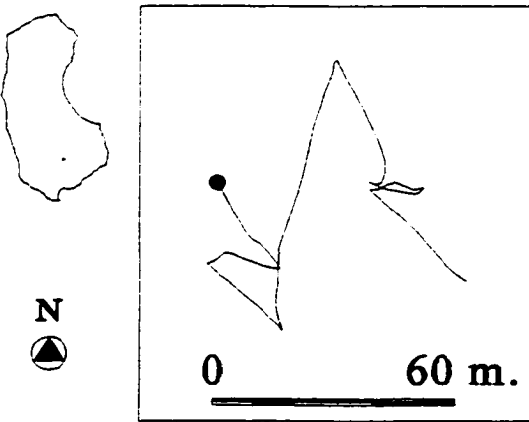
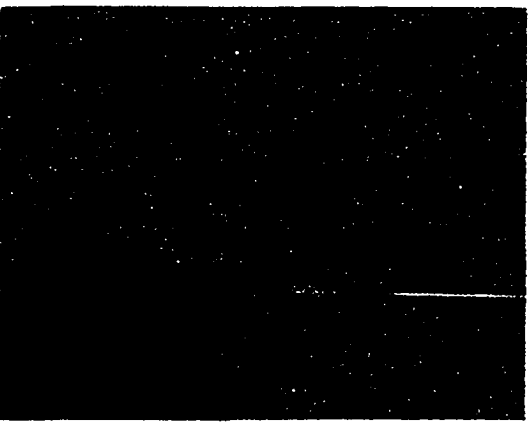
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
042 Mona 	
043 Joanne 	
044 Robin 	

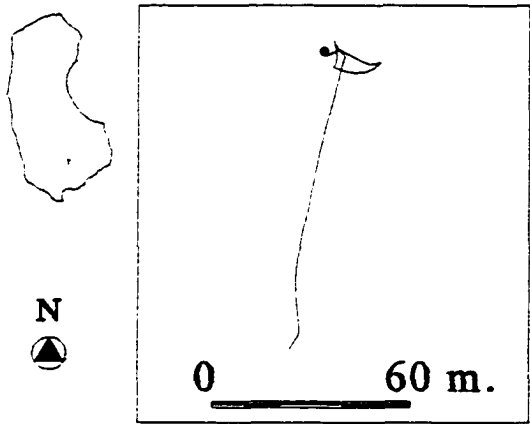
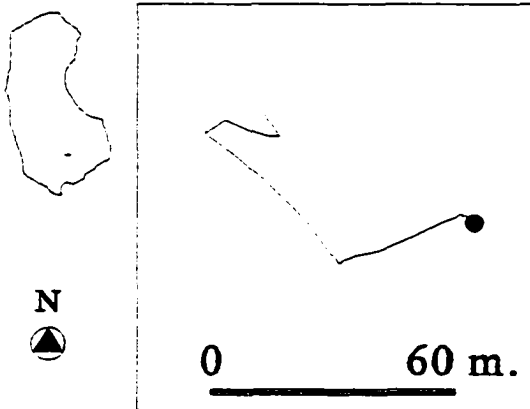
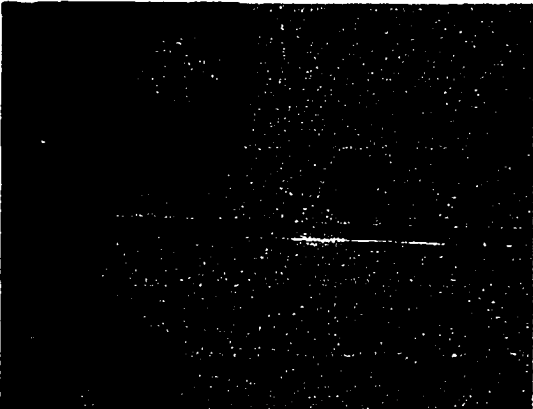
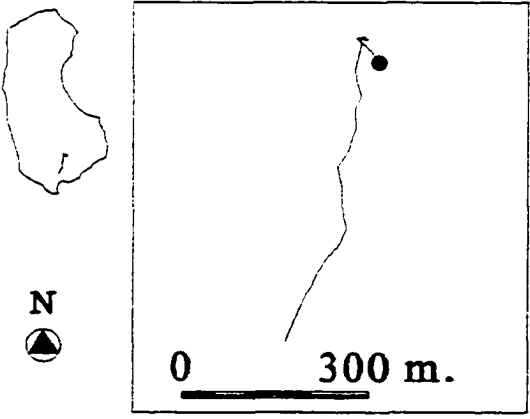
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
045 Karen 	
046 Clem 	
047 Peggy 	

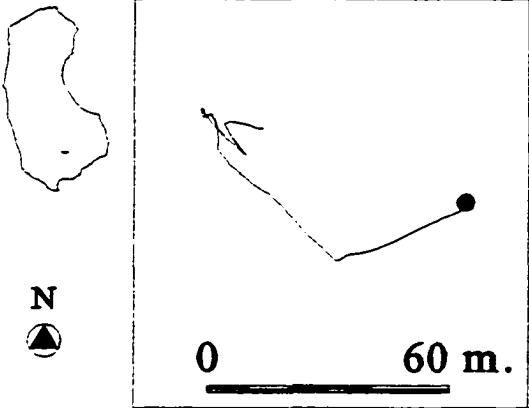
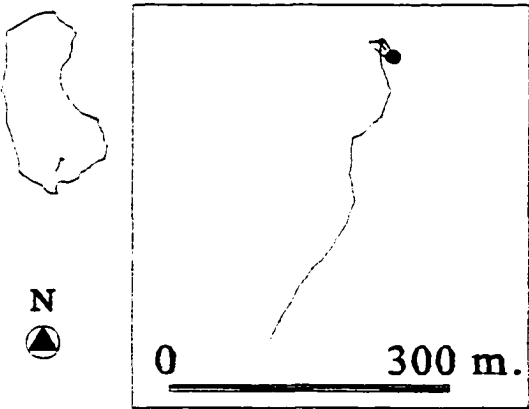
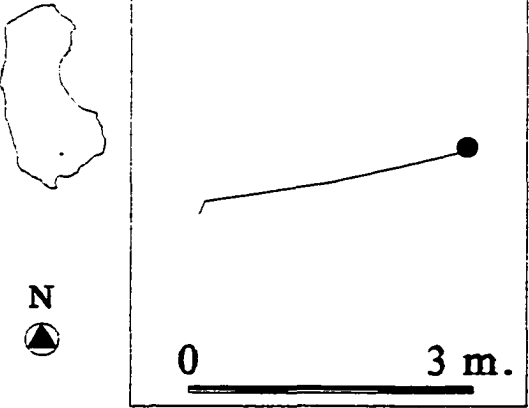
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
048 Mary Ann 	
049 Edna 	
050 Alice 	

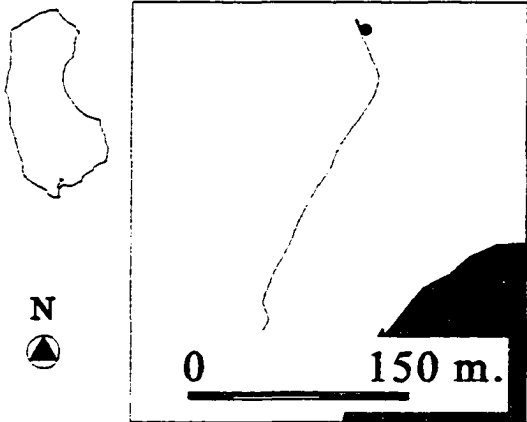
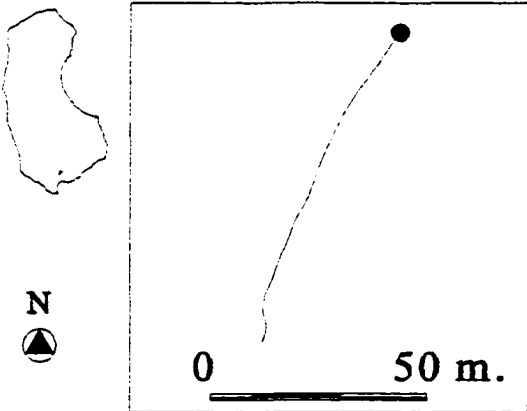
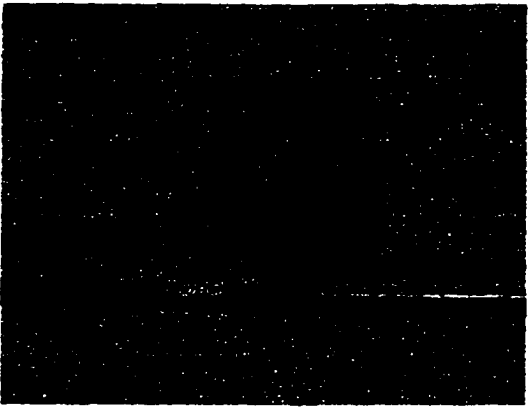
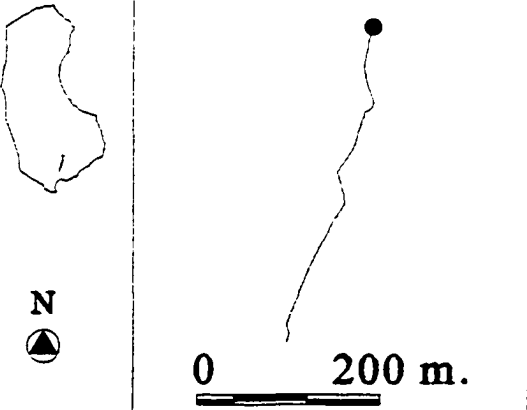
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
051 Barbara  The map for site 051 Barbara includes a small outline of the island of St. John to the left. Below it is a north arrow pointing upwards, labeled 'N'. The main map area shows a trail starting from the bottom and ending at a point marked with a black dot and a small flag icon at the top. A scale bar at the bottom is labeled '0' and '60 m.'.	 A dark, grainy digital photograph of the site. A horizontal white line, likely a 10-centimeter ruler, is visible across the middle of the image for scale.
052 Jennifer  The map for site 052 Jennifer includes a small outline of the island of St. John to the left. Below it is a north arrow pointing upwards, labeled 'N'. The main map area shows a trail starting from the left, moving right, then down, and finally up to a point marked with a black dot. A scale bar at the bottom is labeled '0' and '60 m.'.	 A dark, grainy digital photograph of the site. A horizontal white line, likely a 10-centimeter ruler, is visible across the middle of the image for scale.
053 Shirley  The map for site 053 Shirley includes a small outline of the island of St. John to the left. Below it is a north arrow pointing upwards, labeled 'N'. The main map area shows a trail starting from the bottom and ending at a point marked with a black dot at the top. A scale bar at the bottom is labeled '0' and '300 m.'.	 A dark, grainy digital photograph of the site. A horizontal white line, likely a 10-centimeter ruler, is visible across the middle of the image for scale.

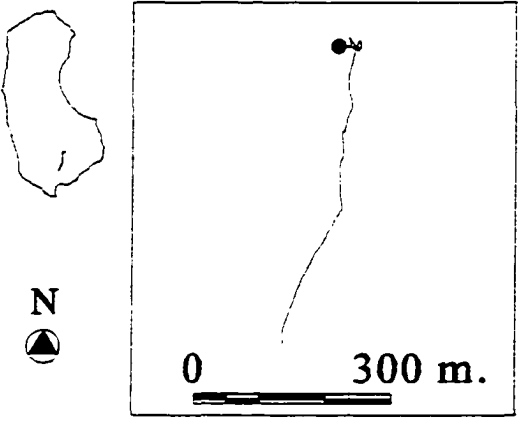
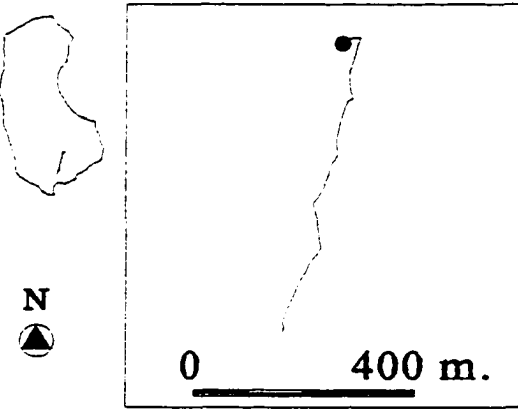
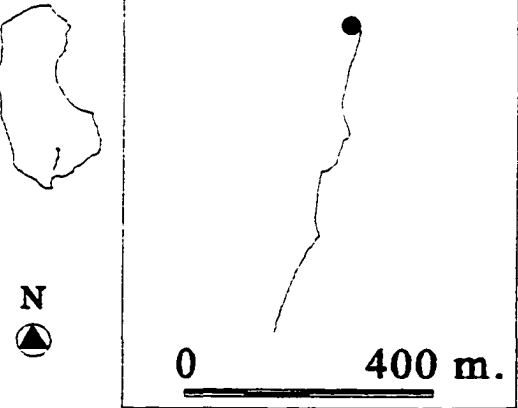
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
054 Janet  The map for Janet rock shows a trail starting from the top left, curving down and then up to a black dot representing the rock. A scale bar at the bottom indicates 0 to 60 meters. A north arrow points upwards.	 A dark, grainy digital image of Janet rock, showing a horizontal line across the middle.
055 Julie  The map for Julie rock shows a trail starting from the bottom left, curving up and then down to a black dot representing the rock. A scale bar at the bottom indicates 0 to 300 meters. A north arrow points upwards.	 A dark, grainy digital image of Julie rock, showing a horizontal line across the middle.
056 Lisa  The map for Lisa rock shows a trail starting from the bottom left, curving up and then down to a black dot representing the rock. A scale bar at the bottom indicates 0 to 3 meters. A north arrow points upwards.	 A dark, grainy digital image of Lisa rock, showing a horizontal line across the middle.

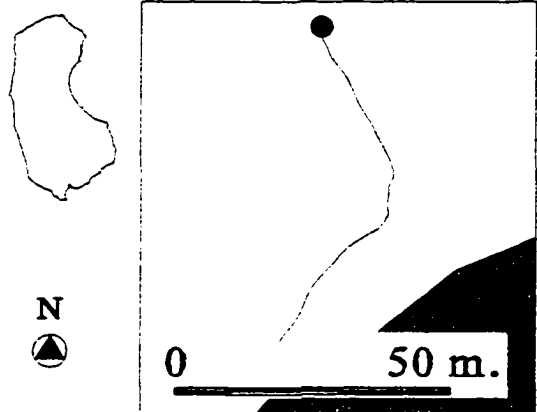
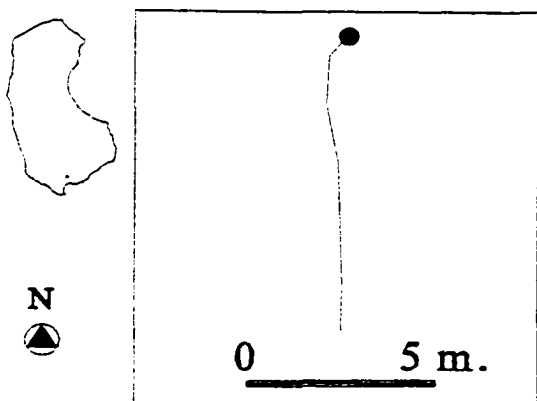
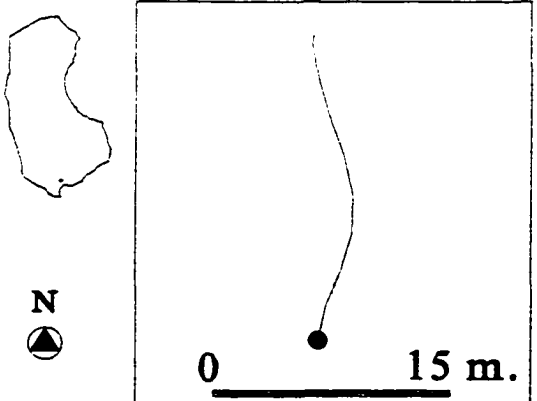
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
057 Susan  The map for Susan rock shows a trail starting from the bottom left and ending at a black dot at the top. A scale bar at the bottom indicates 0 to 150 m. A north arrow is located to the left of the map.	 A dark, grainy digital image of the Susan rock.
058 Rhonda  The map for Rhonda rock shows a trail starting from the bottom left and ending at a black dot at the top. A scale bar at the bottom indicates 0 to 50 m. A north arrow is located to the left of the map.	 A dark, grainy digital image of the Rhonda rock.
059 Irene  The map for Irene rock shows a trail starting from the bottom left and ending at a black dot at the top. A scale bar at the bottom indicates 0 to 200 m. A north arrow is located to the left of the map.	 A dark, grainy digital image of the Irene rock.

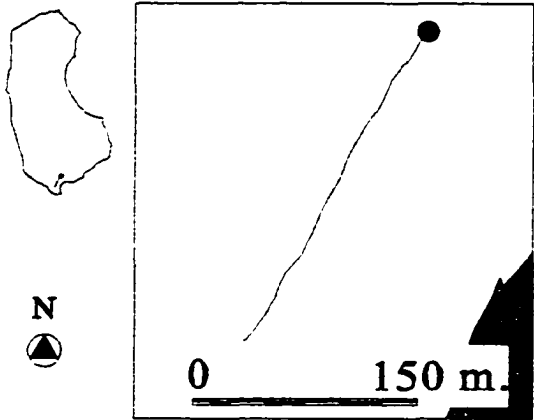
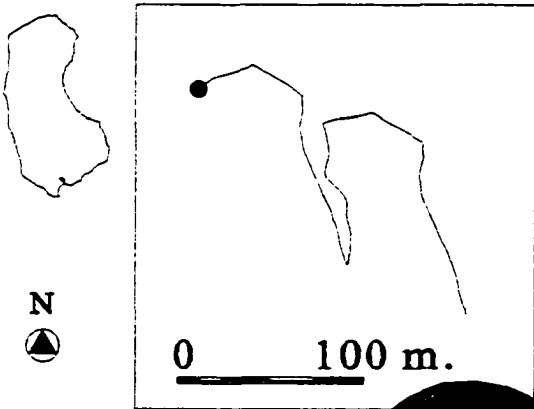
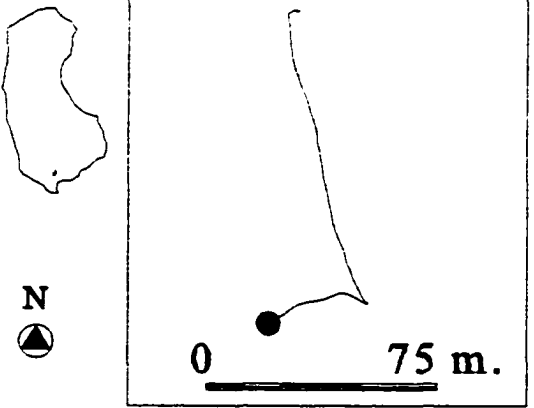
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
060 Rebecca 	
061 Gabby 	
062 Clara 	

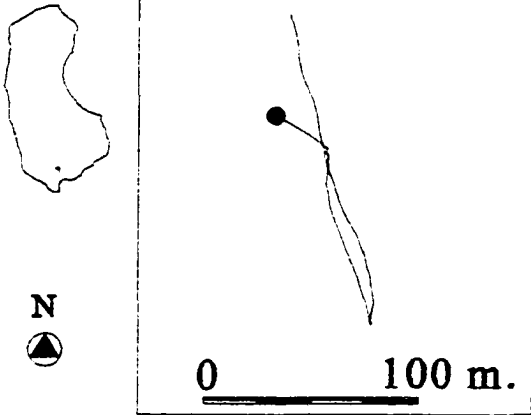
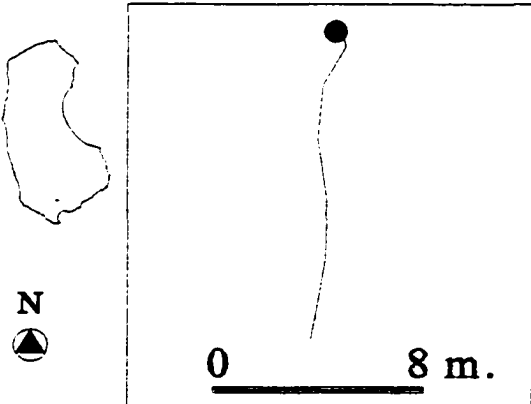
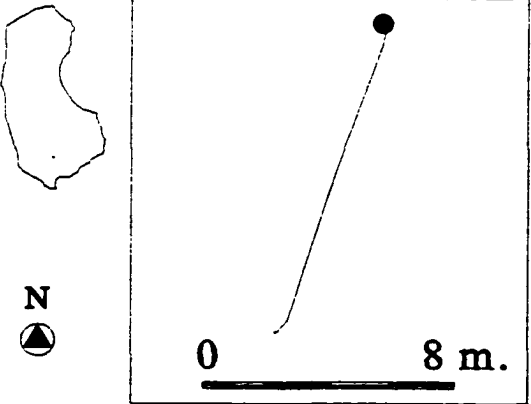
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
063 Marietta 	
064 Xenio 	
068 Leslie 	

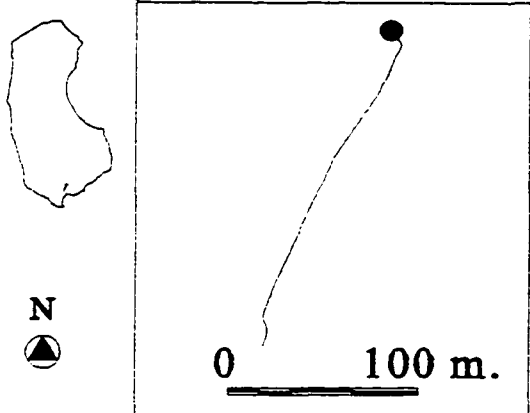
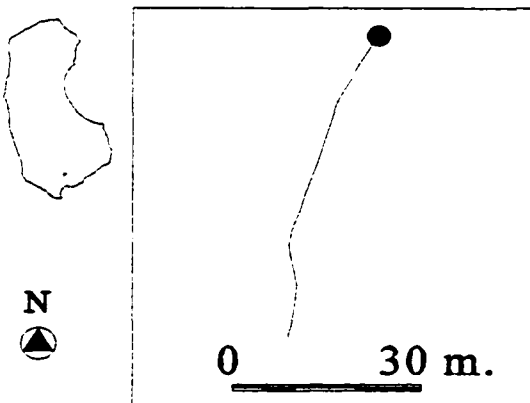
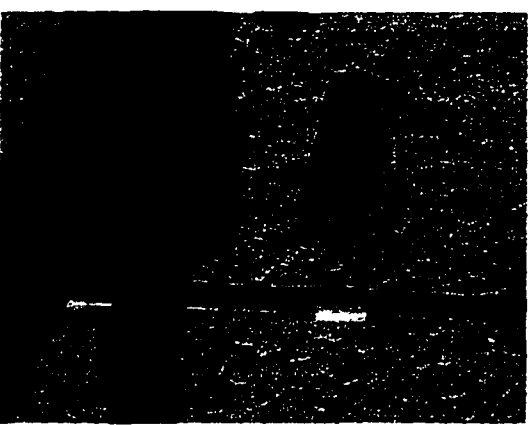
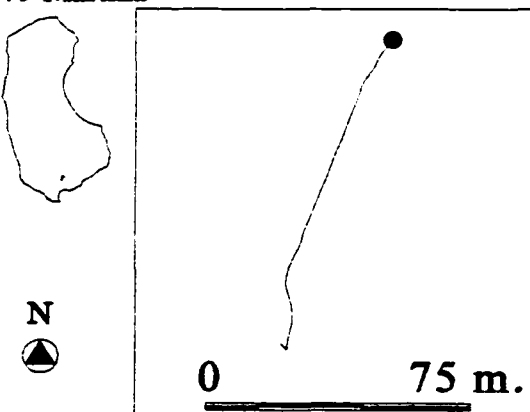
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
069 Sandra 	
070 Linda 	
072 Angel 	

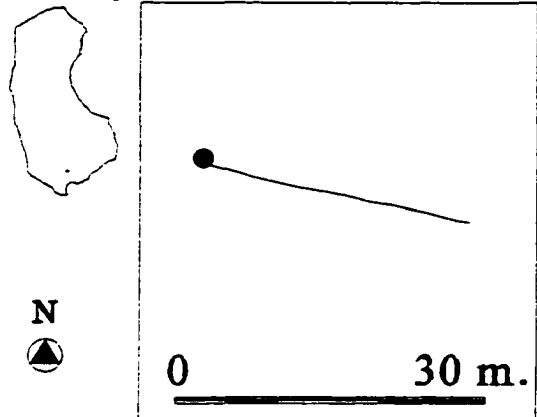
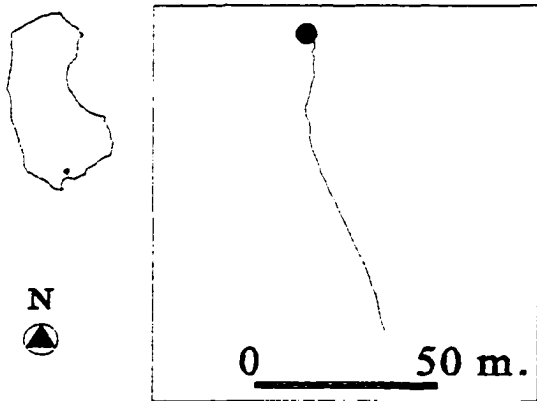
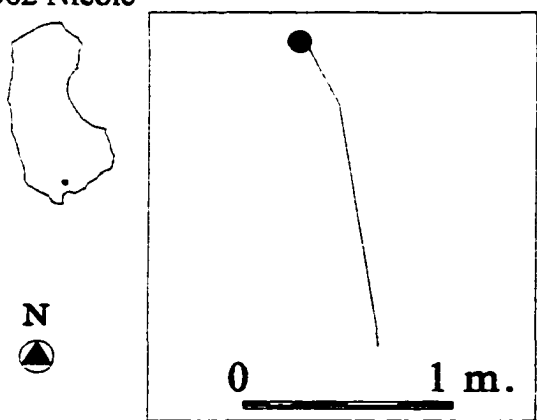
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
073 Claudia  The map for rock 073 Claudia includes a small inset map of the island of Taiwan with a dot indicating the rock's location. The main map shows a trail starting from a point and extending downwards. A scale bar at the bottom indicates a distance of 100 meters. A north arrow is located to the left of the main map, pointing upwards.	 A dark, high-contrast digital image of rock 073 Claudia, showing its irregular shape and texture.
074 Stefanie  The map for rock 074 Stefanie includes a small inset map of the island of Taiwan with a dot indicating the rock's location. The main map shows a trail starting from a point and extending downwards. A scale bar at the bottom indicates a distance of 8 meters. A north arrow is located to the left of the main map, pointing upwards.	 A dark, high-contrast digital image of rock 074 Stefanie, showing its irregular shape and texture.
075 Stella  The map for rock 075 Stella includes a small inset map of the island of Taiwan with a dot indicating the rock's location. The main map shows a trail starting from a point and extending downwards. A scale bar at the bottom indicates a distance of 8 meters. A north arrow is located to the left of the main map, pointing upwards.	 A dark, high-contrast digital image of rock 075 Stella, showing its irregular shape and texture.

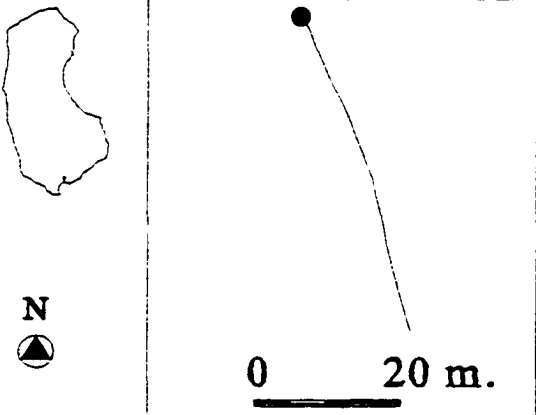
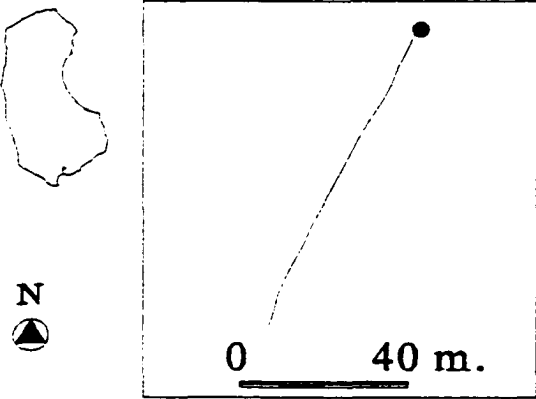
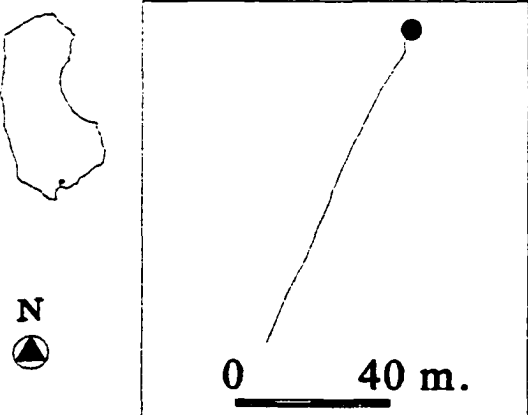
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
077 Tammy 	
078 Lottie 	
079 Martina 	

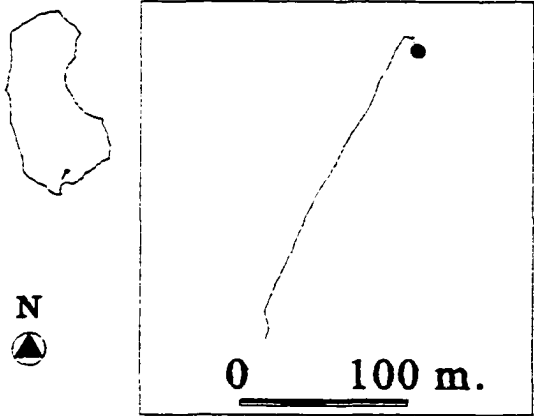
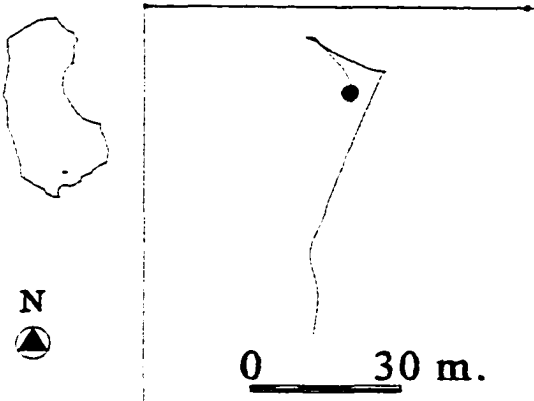
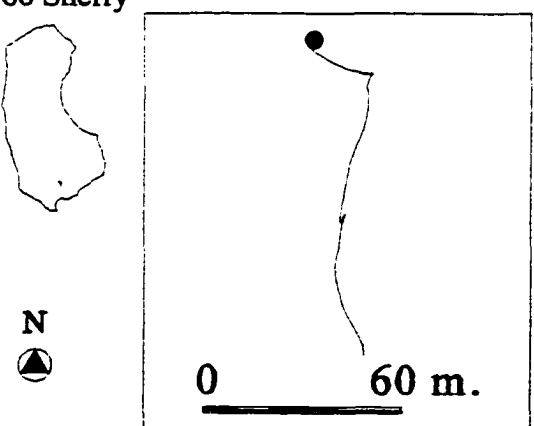
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
080 Sheryl 	
081 Katie 	
082 Nicole 	

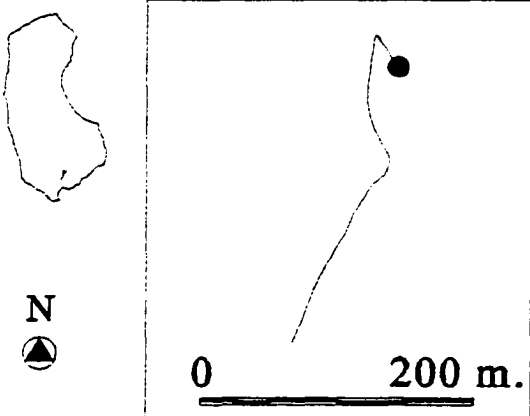
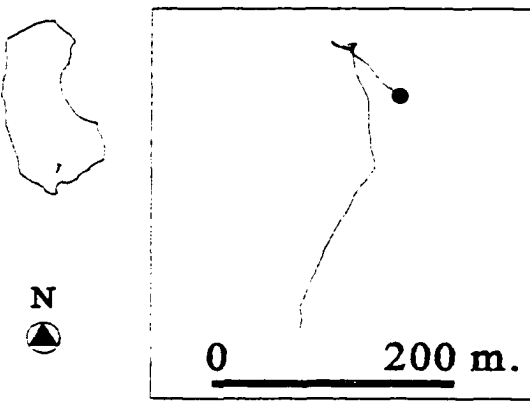
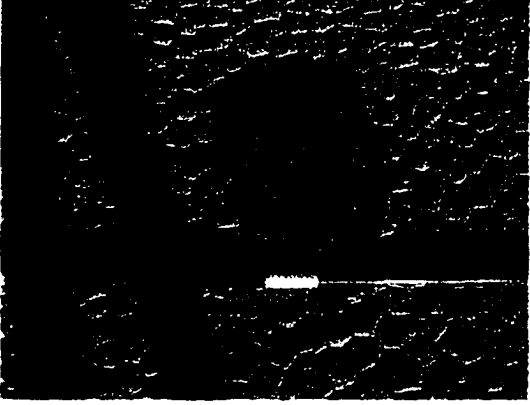
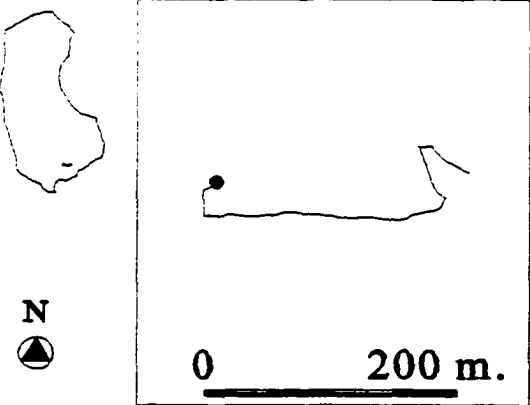
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
083 Eileen 	
084 Josephine 	
085 Matilda 	

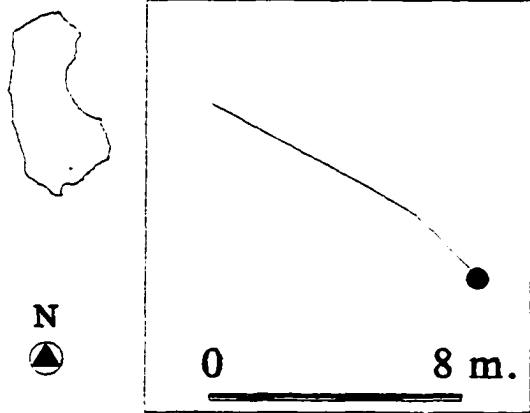
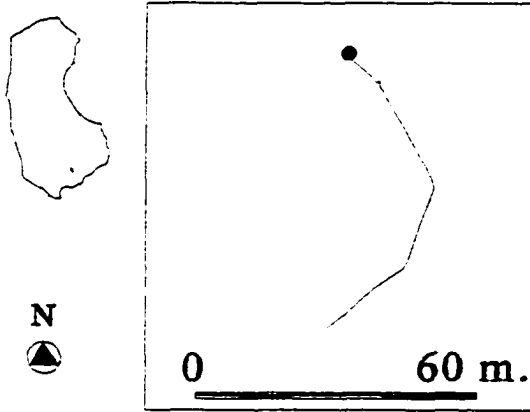
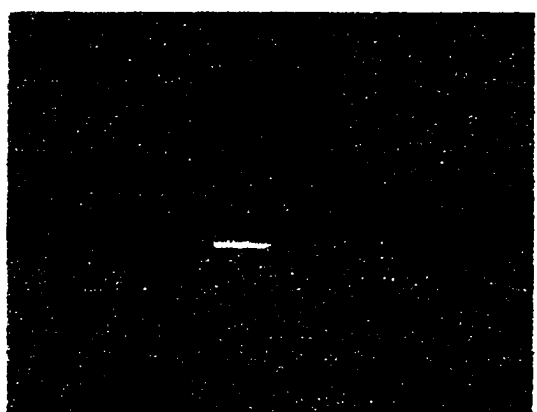
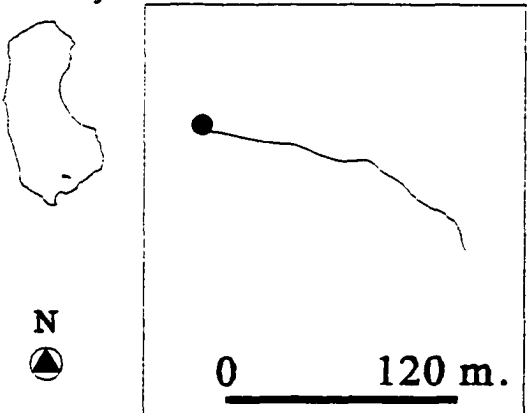
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
086 Patricia 	
087 Nilufer 	
088 Sherry 	

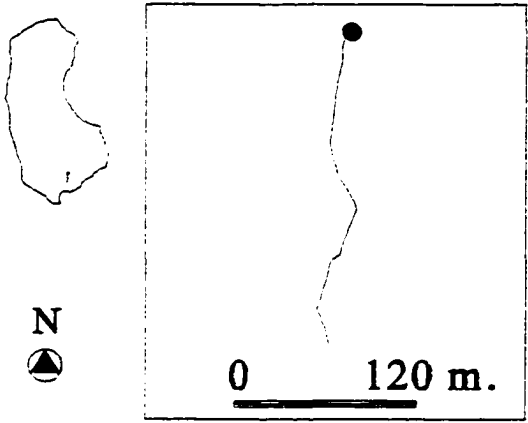
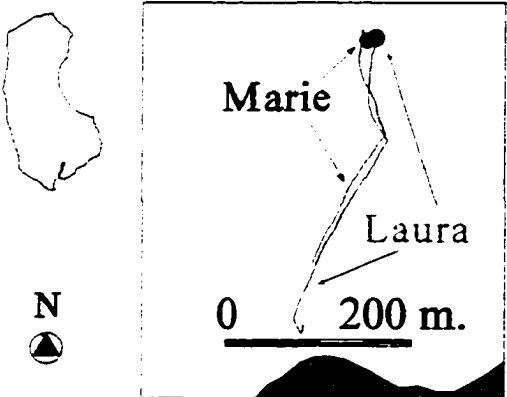
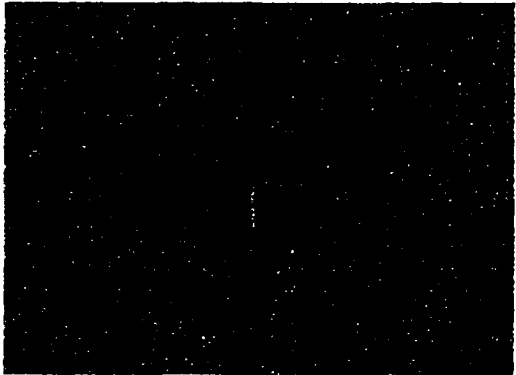
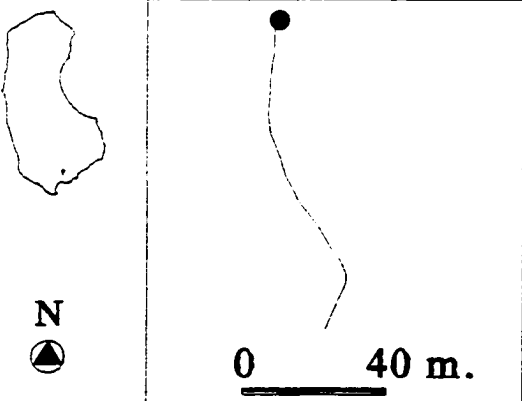
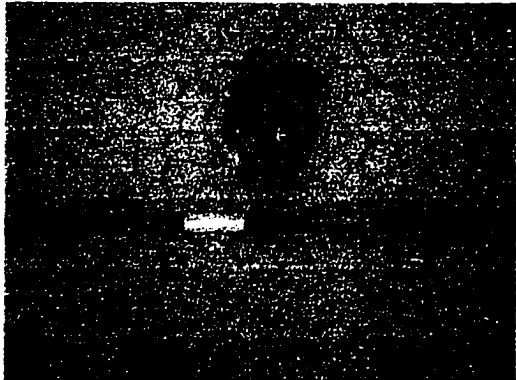
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
089 Bep  The map for Bep shows a small inset map of the island of Hawaii with a dot in the southern part. The main map shows a trail starting from the bottom left, going up and then right, ending at a black dot. A north arrow points up, and a scale bar indicates 0 to 200 m.	 A dark, grainy digital image of the Bep rock site. A horizontal white line, likely a 10-centimeter ruler, is visible in the lower center of the image.
090 Glenda  The map for Glenda shows a small inset map of the island of Hawaii with a dot in the southern part. The main map shows a trail starting from the bottom left, going up and then right, ending at a black dot. A north arrow points up, and a scale bar indicates 0 to 200 m.	 A dark, grainy digital image of the Glenda rock site. A horizontal white line, likely a 10-centimeter ruler, is visible in the lower center of the image.
091 Ellen  The map for Ellen shows a small inset map of the island of Hawaii with a dot in the southern part. The main map shows a trail starting from the bottom left, going up and then right, ending at a black dot. A north arrow points up, and a scale bar indicates 0 to 200 m.	 A dark, grainy digital image of the Ellen rock site. A horizontal white line, likely a 10-centimeter ruler, is visible in the lower center of the image.

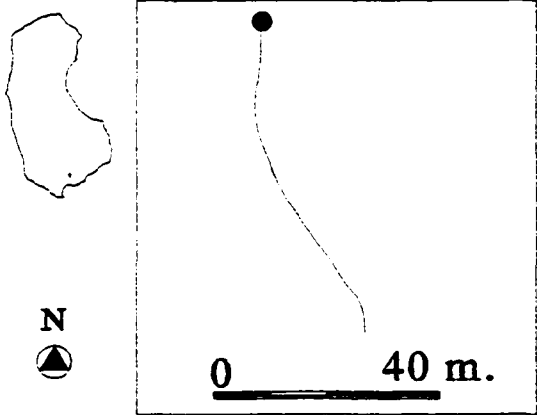
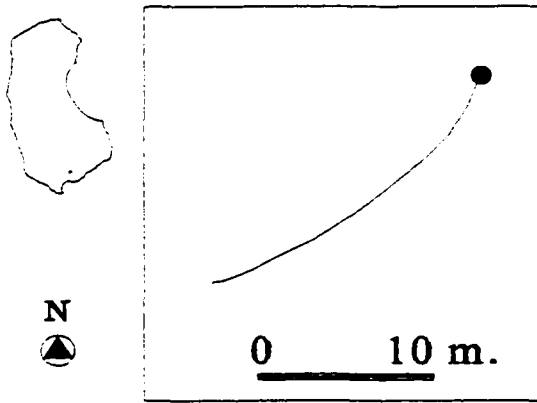
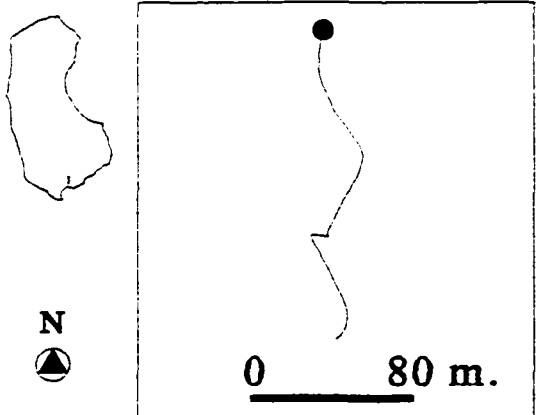
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
092 Ossie 	
093 Bessie 	
094 Kitty 	

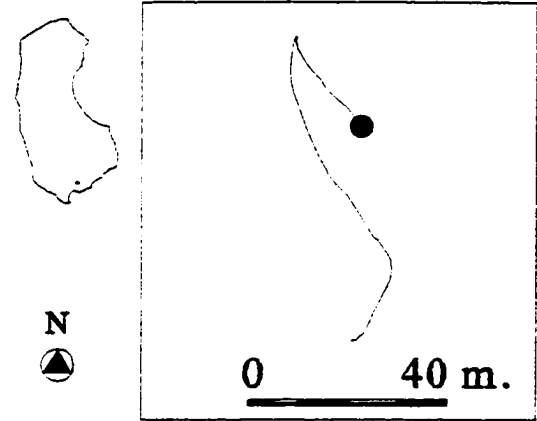
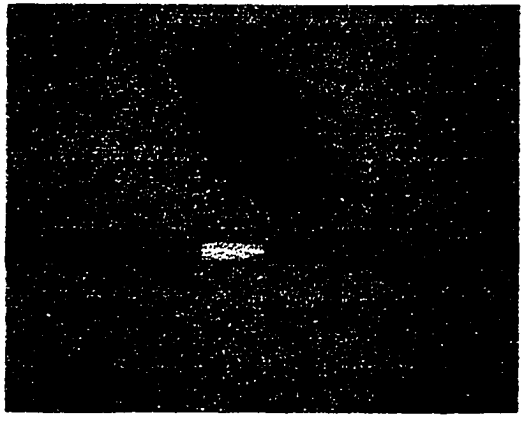
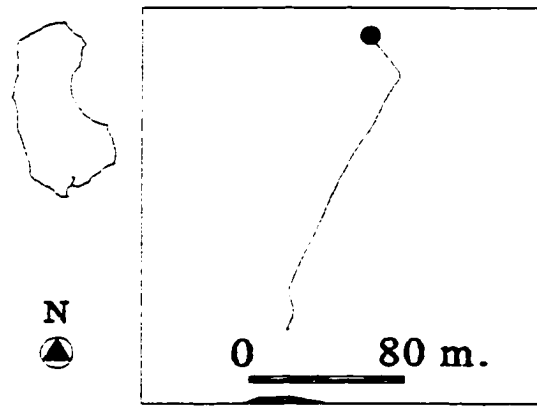
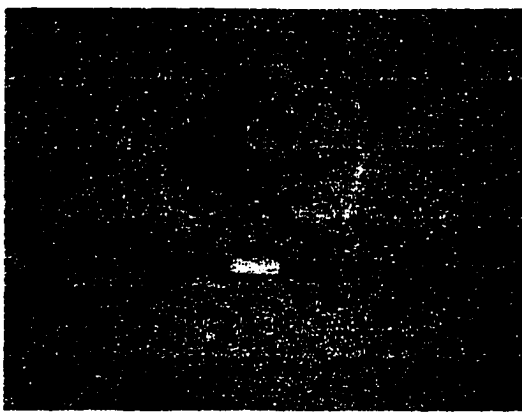
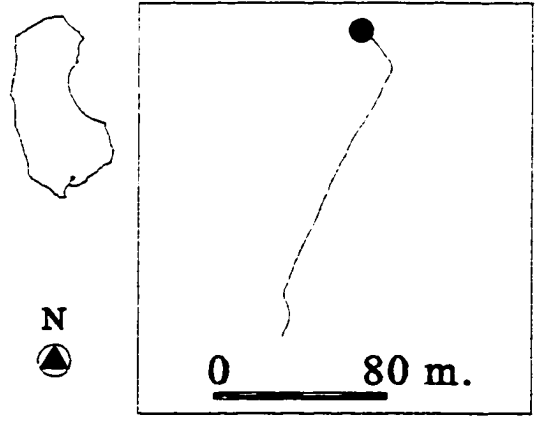
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
095 Celia 	
096 Marie/ 097 Laura 	
099 Margot 	

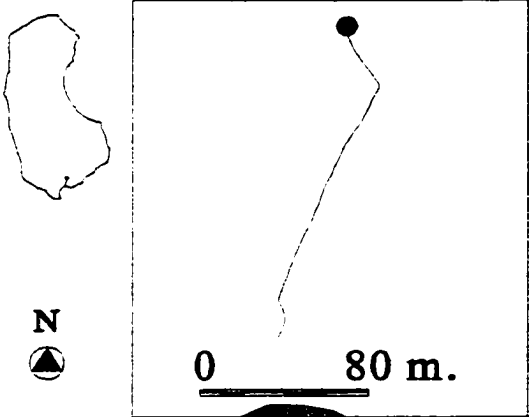
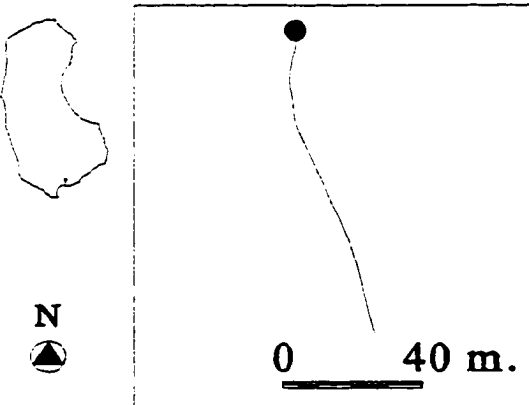
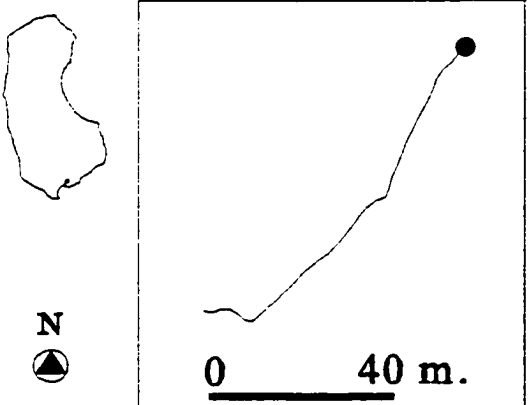
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale. Images of Celia (#95) and Margot (#99) are oriented with north to the left; the image of Marie (#96) and Laura (#97) shows north at the top.

Rock Number/Name and Trail Map	Digital Image
100 Chantal  The map for Chantal rock includes a small inset map of the island of Tahiti with a dot indicating the rock's location. The main map shows a trail starting from a black dot at the top and curving downwards and to the right. A north arrow is located to the left of the main map, and a scale bar at the bottom indicates a distance of 40 meters.	 A black and white photograph of Chantal rock, showing a dark, craggy rock face with a small, light-colored feature near the bottom center.
101 Elizabeth  The map for Elizabeth rock includes a small inset map of the island of Tahiti with a dot indicating the rock's location. The main map shows a trail starting from a black dot at the bottom left and curving upwards and to the right. A north arrow is located to the left of the main map, and a scale bar at the bottom indicates a distance of 10 meters.	 A black and white photograph of Elizabeth rock, showing a dark, craggy rock face with a small, light-colored feature near the bottom center.
102 Anne  The map for Anne rock includes a small inset map of the island of Tahiti with a dot indicating the rock's location. The main map shows a trail starting from a black dot at the top and curving downwards and to the left. A north arrow is located to the left of the main map, and a scale bar at the bottom indicates a distance of 80 meters.	 A black and white photograph of Anne rock, showing a dark, craggy rock face with a small, light-colored feature near the bottom center.

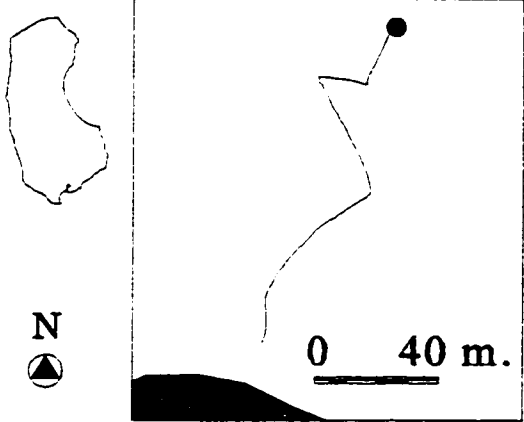
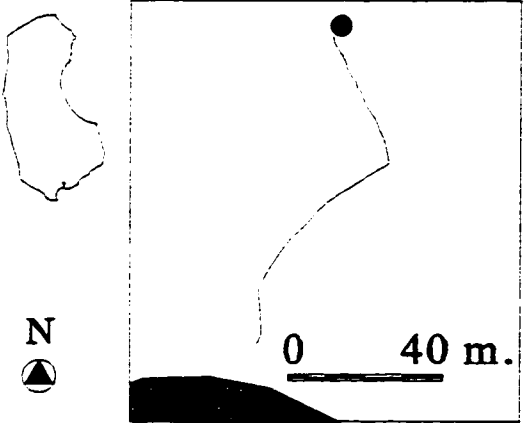
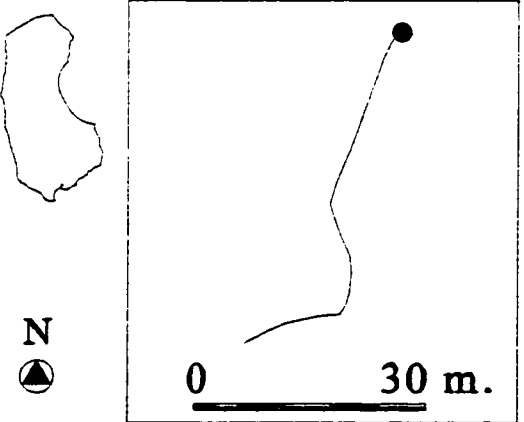
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
103 Caroline  The map for Caroline rock includes a small inset map of the island of St. John, a north arrow pointing up, and a scale bar from 0 to 40 meters. The trail is shown as a dashed line starting from the bottom left and ending at a black dot representing the rock.	 A dark, grainy digital photograph of the Caroline rock, showing a small, light-colored rock formation in the center.
104 Betty  The map for Betty rock includes a small inset map of the island of St. John, a north arrow pointing up, and a scale bar from 0 to 80 meters. The trail is shown as a dashed line starting from the bottom left and ending at a black dot representing the rock.	 A dark, grainy digital photograph of the Betty rock, showing a small, light-colored rock formation in the center.
105 Wilma  The map for Wilma rock includes a small inset map of the island of St. John, a north arrow pointing up, and a scale bar from 0 to 80 meters. The trail is shown as a dashed line starting from the bottom left and ending at a black dot representing the rock.	 A dark, grainy digital photograph of the Wilma rock, showing a small, light-colored rock formation in the center.

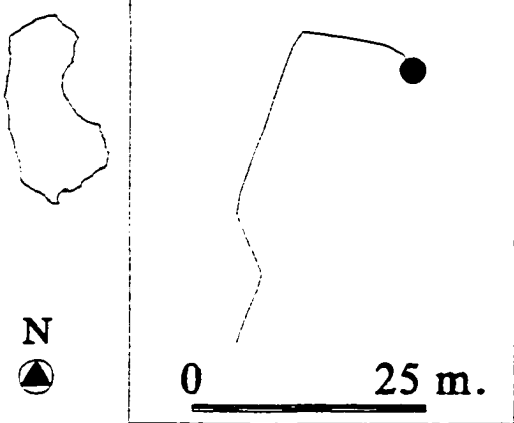
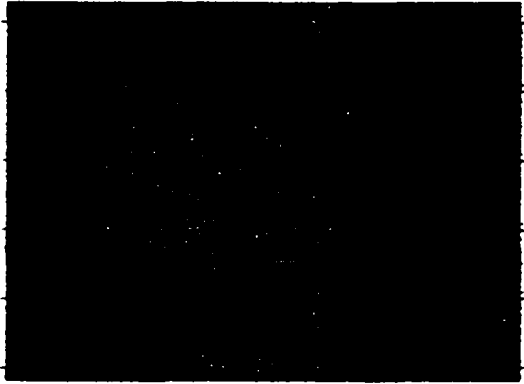
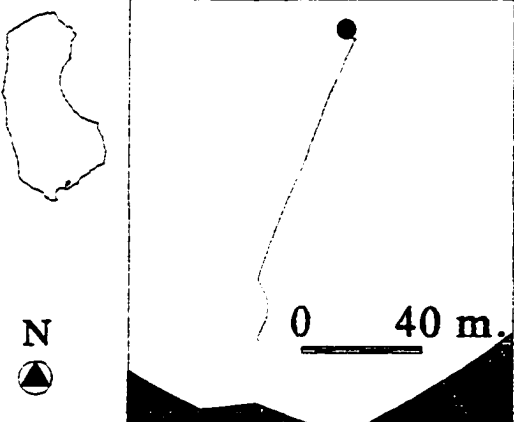
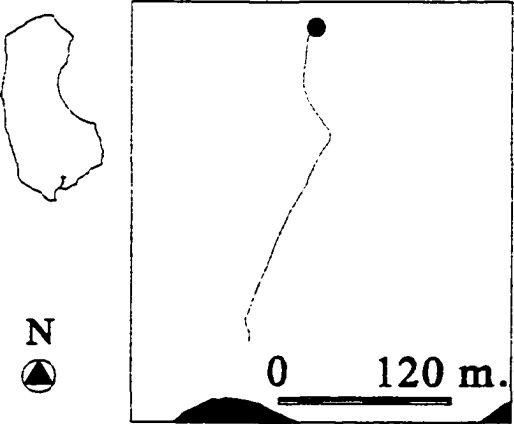
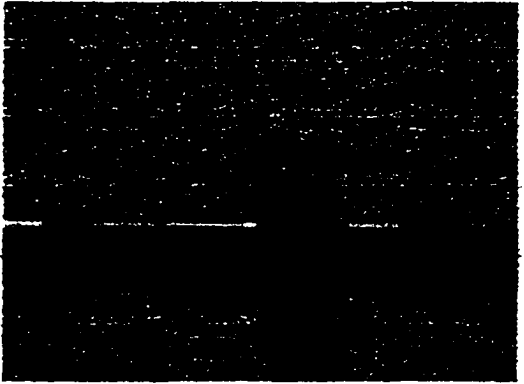
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
106 Dottie 	
107 Trish 	
108 Rolanda 	

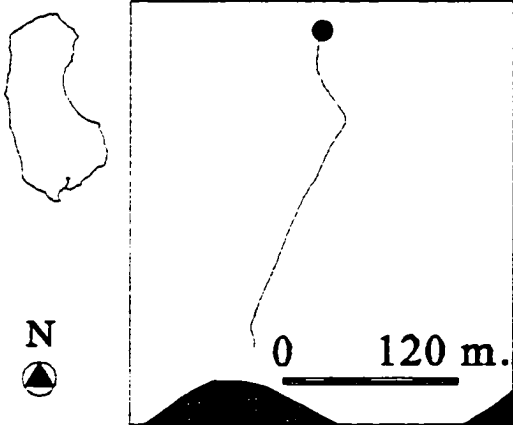
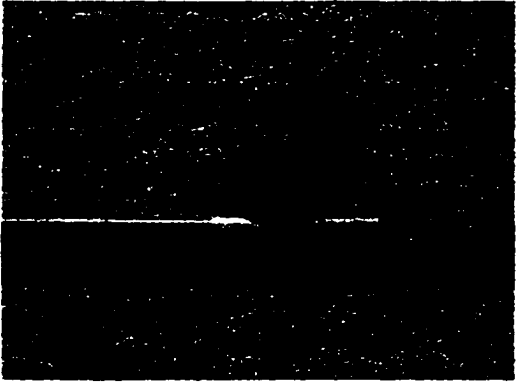
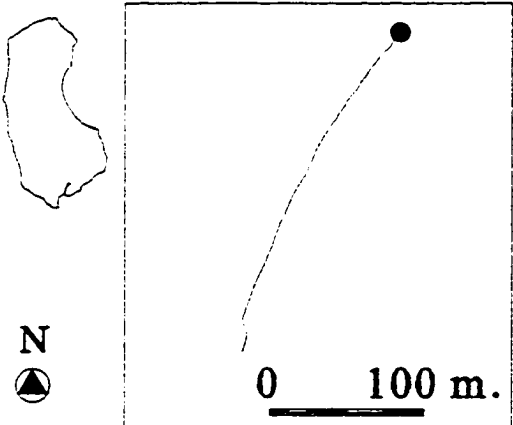
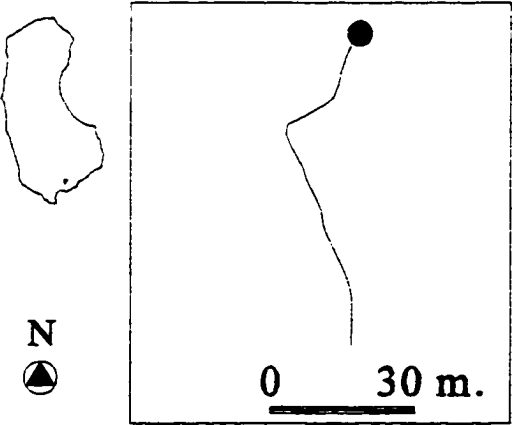
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
109 Margaret  The map for Margaret (109) shows a winding trail starting from a shaded area at the bottom left, moving upwards with several turns, and ending at a black dot at the top right. A north arrow points upwards, and a scale bar indicates 0 to 40 meters.	
110 Sara  The map for Sara (110) shows a winding trail starting from a shaded area at the bottom left, moving upwards with several turns, and ending at a black dot at the top right. A north arrow points upwards, and a scale bar indicates 0 to 40 meters.	
111 Martha  The map for Martha (111) shows a winding trail starting from a shaded area at the bottom left, moving upwards with several turns, and ending at a black dot at the top right. A north arrow points upwards, and a scale bar indicates 0 to 30 meters.	

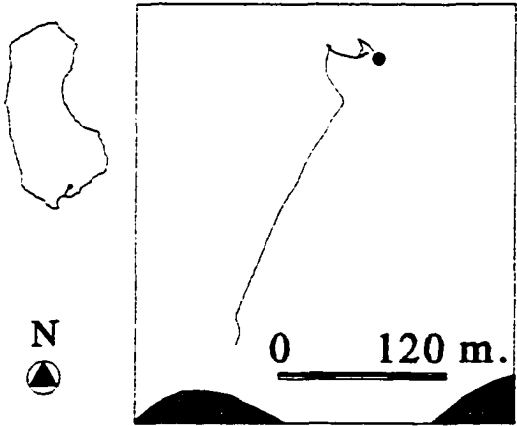
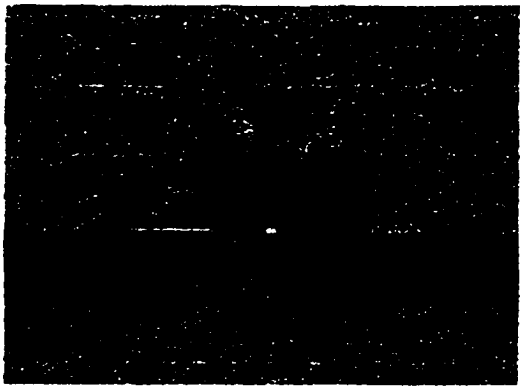
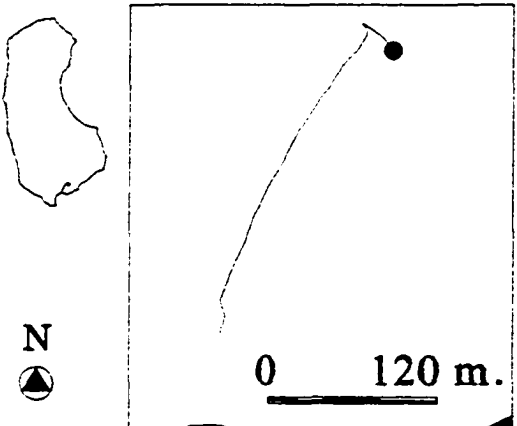
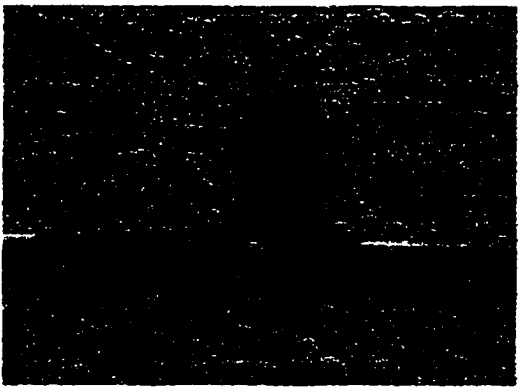
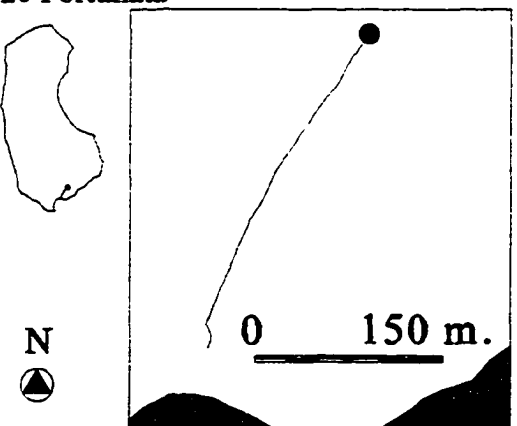
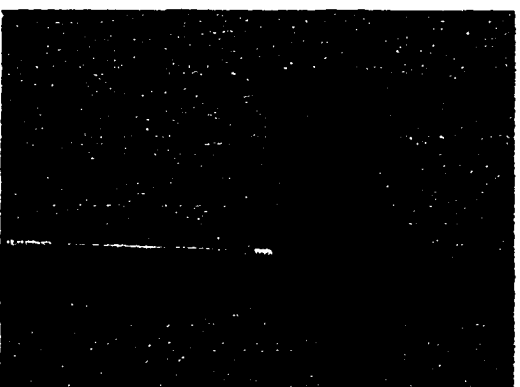
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
112 Rosemarie  The map for Rosemarie shows a trail starting from the bottom left, going up and then right to a black dot. A scale bar at the bottom indicates 0 to 25 m. A north arrow is in the bottom left, and a small inset map of the island is in the top left.	 A dark, grainy digital image of the Rosemarie rock, showing a dark, irregular shape against a lighter background.
113 Sylvia  The map for Sylvia shows a trail starting from the bottom left, going up and then right to a black dot. A scale bar at the bottom indicates 0 to 40 m. A north arrow is in the bottom left, and a small inset map of the island is in the top left.	 A dark, grainy digital image of the Sylvia rock, showing a dark, irregular shape against a lighter background.
114 Minnie  The map for Minnie shows a trail starting from the bottom left, going up and then right to a black dot. A scale bar at the bottom indicates 0 to 120 m. A north arrow is in the bottom left, and a small inset map of the island is in the top left.	 A dark, grainy digital image of the Minnie rock, showing a dark, irregular shape against a lighter background.

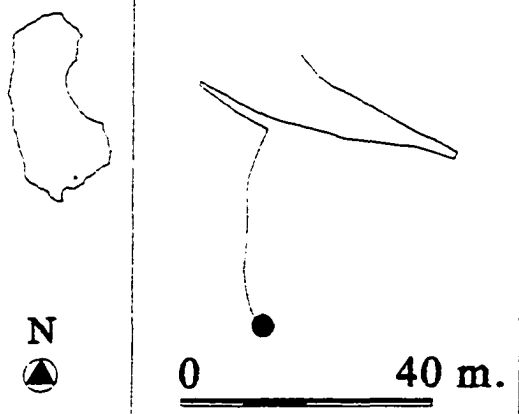
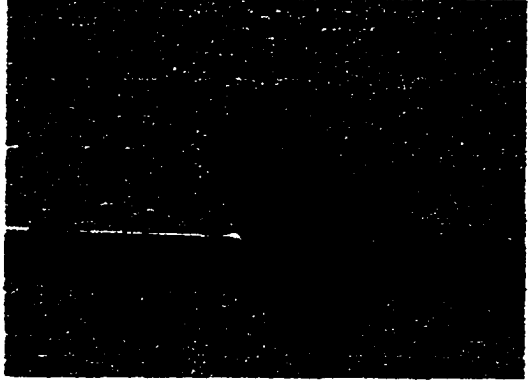
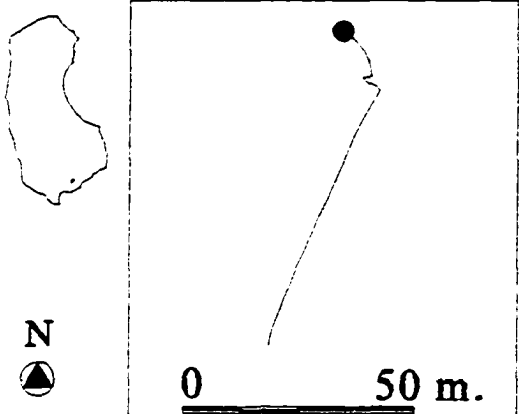
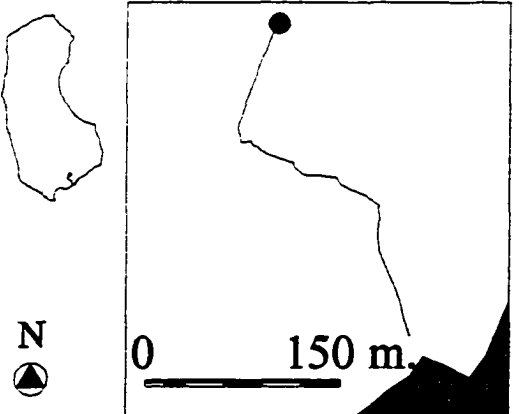
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
115 Denise 	
116 Hortense 	
117 Lina 	

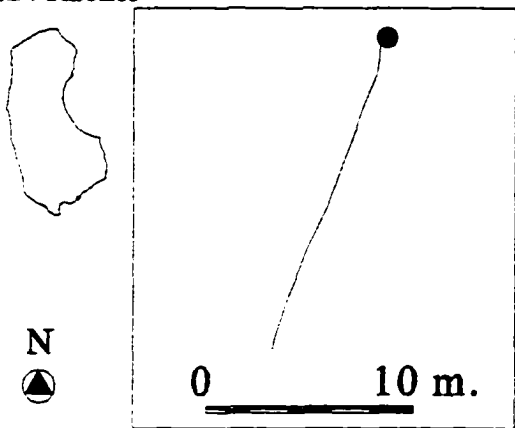
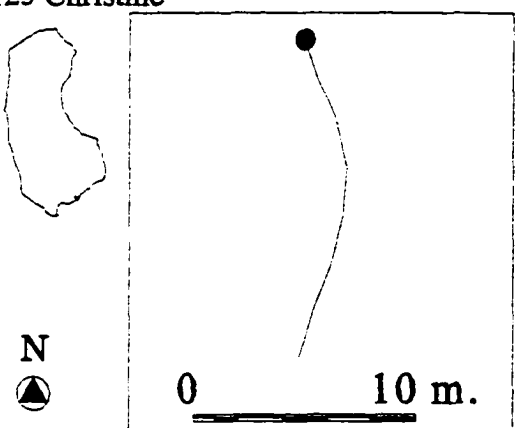
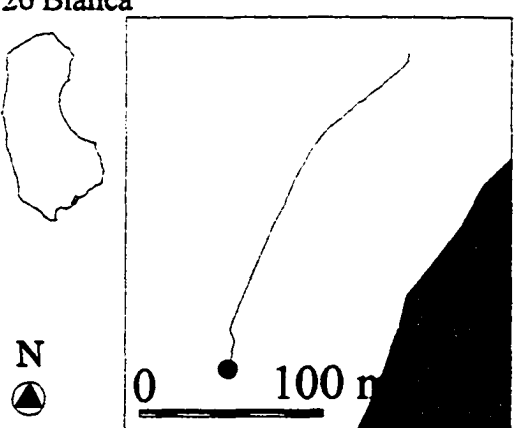
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
118 Sharon 	
119 Heather 	
120 Fortunata 	

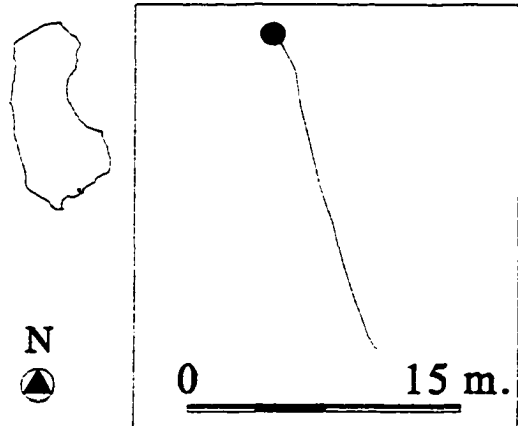
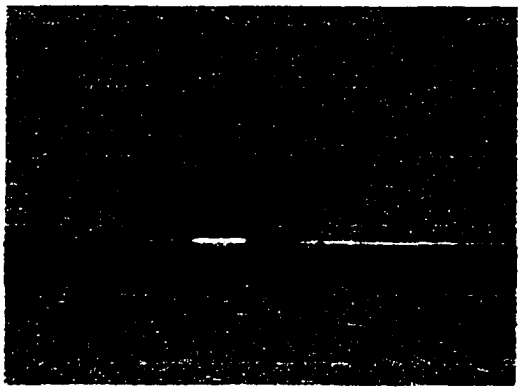
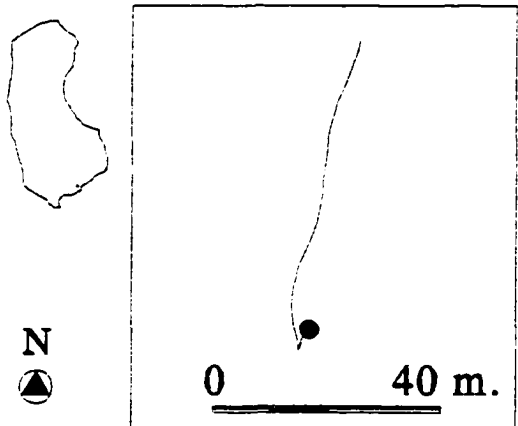
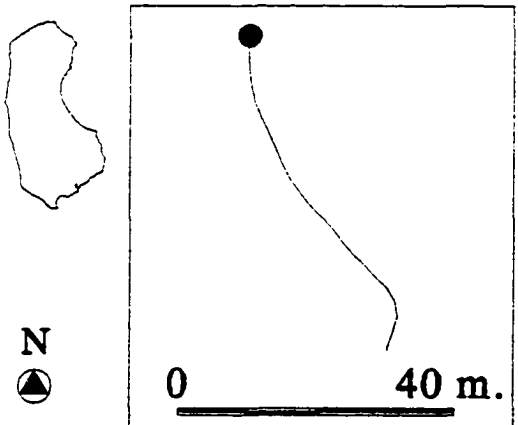
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
121 Rose 	
122 Marlene 	
123 Amanda 	

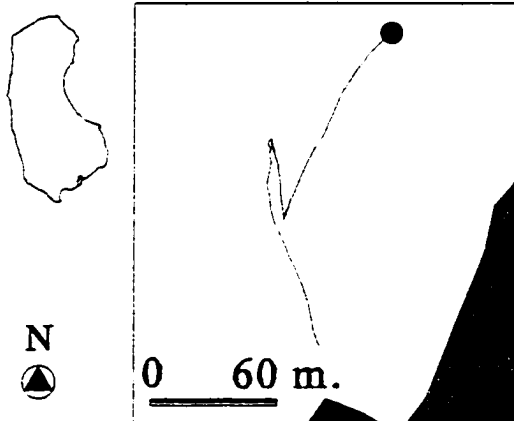
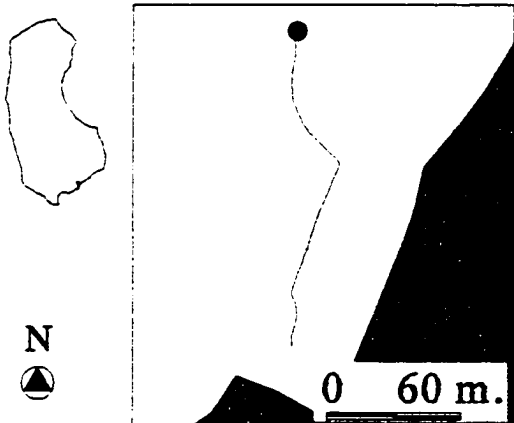
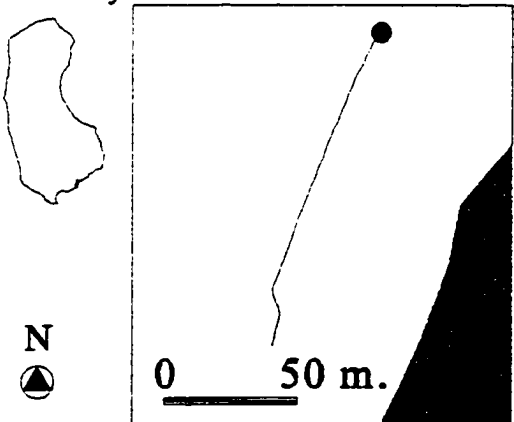
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
124 Rachel  The map for Rachel shows a trail line starting from a point at the bottom left and extending diagonally upwards to a black dot at the top right. A scale bar at the bottom indicates 0 to 10 m. A north arrow is located to the left of the map.	 A dark, high-contrast digital image of the Rachel rock, showing a light-colored, irregularly shaped rock against a dark background.
125 Christine  The map for Christine shows a trail line starting from a point at the bottom left and extending diagonally upwards to a black dot at the top right. A scale bar at the bottom indicates 0 to 10 m. A north arrow is located to the left of the map.	 A dark, high-contrast digital image of the Christine rock, showing a light-colored, irregularly shaped rock against a dark background.
126 Blanca  The map for Blanca shows a trail line starting from a point at the bottom left and extending diagonally upwards to a black dot at the top right. A scale bar at the bottom indicates 0 to 100 m. A north arrow is located to the left of the map.	 A dark, high-contrast digital image of the Blanca rock, showing a light-colored, irregularly shaped rock against a dark background.

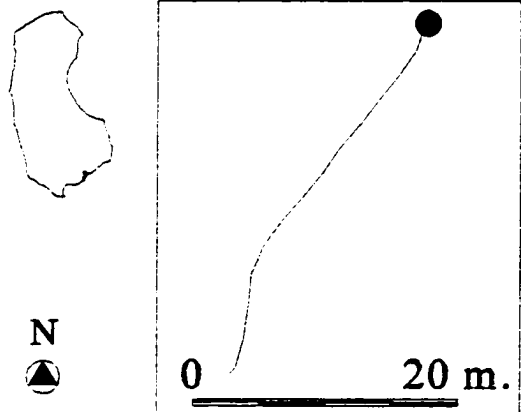
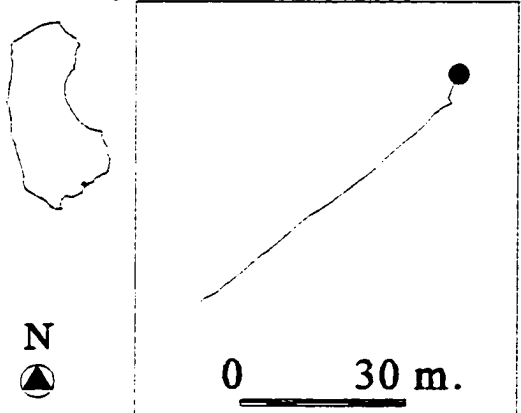
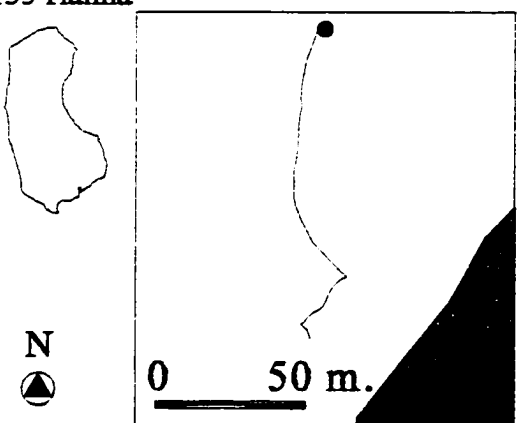
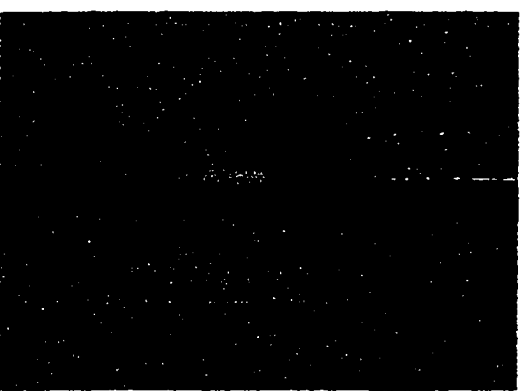
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
127 Mamie 	
128 Carol 	
129 Esther 	

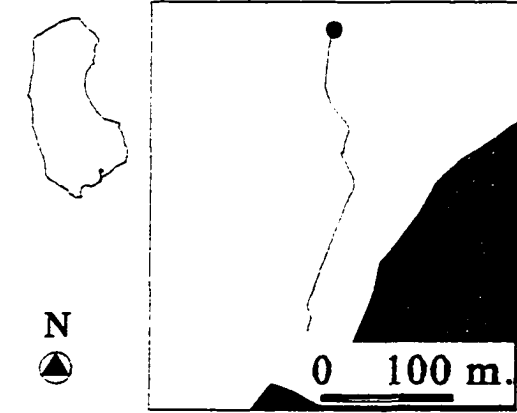
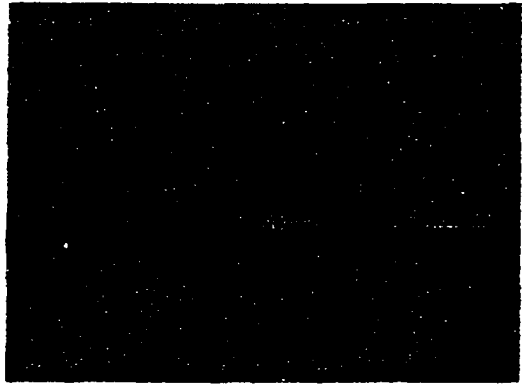
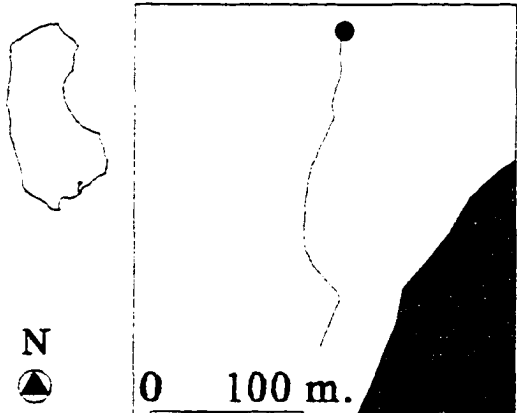
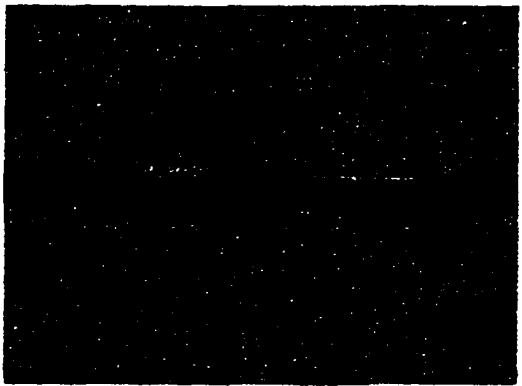
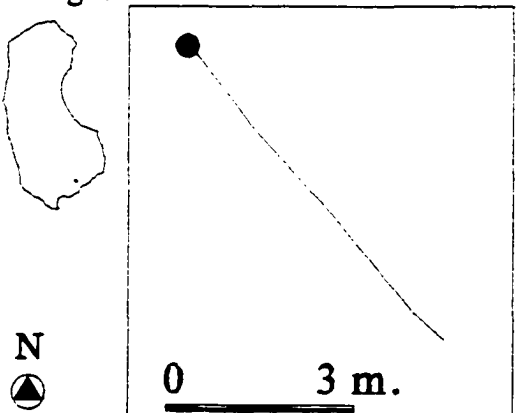
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
130 Andrea  The map for rock 130 Andrea includes a small inset map of the island of St. Helena in the top left corner. The main map shows a trail starting from the bottom left, moving upwards, and then branching to the right towards a black dot representing the rock. A north arrow is located in the bottom left corner, pointing upwards. A scale bar at the bottom indicates 0 to 60 meters.	 A dark, grainy digital photograph of rock 130 Andrea. The rock is a dark, irregular shape against a lighter, textured background.
131 Brianna  The map for rock 131 Brianna includes a small inset map of the island of St. Helena in the top left corner. The main map shows a trail starting from the bottom left, moving upwards, and then branching to the right towards a black dot representing the rock. A north arrow is located in the bottom left corner, pointing upwards. A scale bar at the bottom indicates 0 to 60 meters.	 A dark, grainy digital photograph of rock 131 Brianna. The rock is a dark, irregular shape against a lighter, textured background.
132 Goldy  The map for rock 132 Goldy includes a small inset map of the island of St. Helena in the top left corner. The main map shows a trail starting from the bottom left, moving upwards, and then branching to the right towards a black dot representing the rock. A north arrow is located in the bottom left corner, pointing upwards. A scale bar at the bottom indicates 0 to 50 meters.	 A dark, grainy digital photograph of rock 132 Goldy. The rock is a dark, irregular shape against a lighter, textured background.

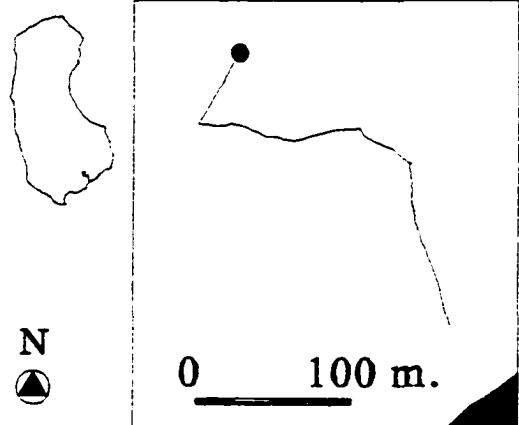
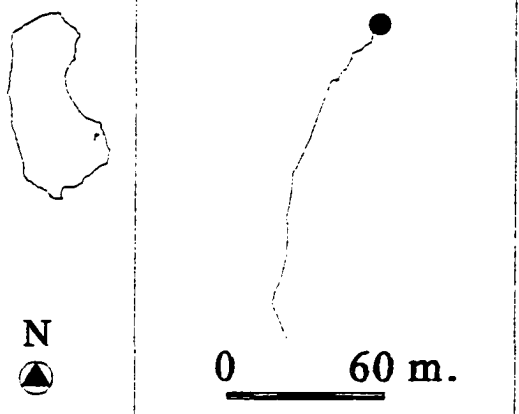
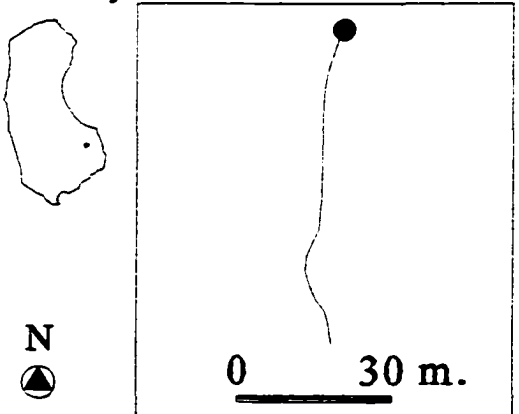
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
133 Jill  The map for rock 133 Jill shows a trail starting from the bottom left, curving upwards and to the right, ending at a black dot. A north arrow is located to the left of the trail. A scale bar at the bottom indicates 0 to 20 meters.	 A dark, grainy digital image of rock 133 Jill, showing a horizontal line of light-colored material against a dark background.
134 Molly  The map for rock 134 Molly shows a trail starting from the bottom left, curving upwards and to the right, ending at a black dot. A north arrow is located to the left of the trail. A scale bar at the bottom indicates 0 to 30 meters.	 A dark, grainy digital image of rock 134 Molly, showing a horizontal line of light-colored material against a dark background.
135 Hanna  The map for rock 135 Hanna shows a trail starting from the bottom left, curving upwards and to the right, ending at a black dot. A north arrow is located to the left of the trail. A scale bar at the bottom indicates 0 to 50 meters.	 A dark, grainy digital image of rock 135 Hanna, showing a horizontal line of light-colored material against a dark background.

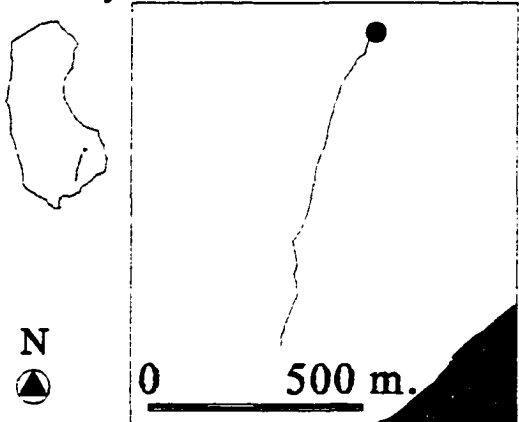
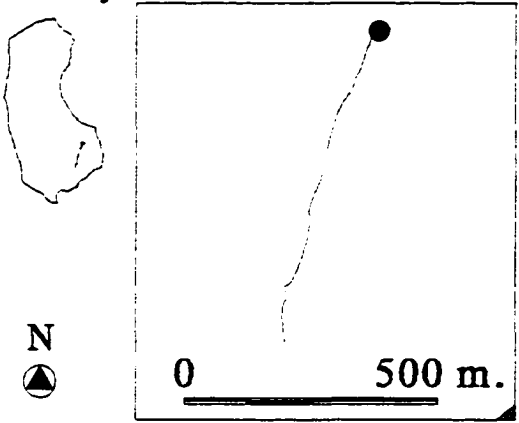
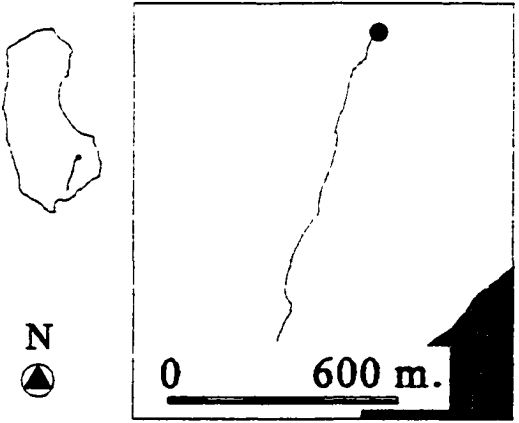
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
137 Carmina  The map for Carmina rock includes a small inset map of the island of Taiwan on the left, with a dot indicating the rock's location. The main map shows a trail starting from a black dot at the top and winding down to the right. A scale bar at the bottom indicates 0 to 100 meters. A north arrow is located at the bottom left.	 A dark, grainy digital photograph of the Carmina rock, showing its irregular shape and texture.
138 Florence  The map for Florence rock includes a small inset map of the island of Taiwan on the left, with a dot indicating the rock's location. The main map shows a trail starting from a black dot at the top and winding down to the right. A scale bar at the bottom indicates 0 to 100 meters. A north arrow is located at the bottom left.	 A dark, grainy digital photograph of the Florence rock, showing its irregular shape and texture.
139 Agnes  The map for Agnes rock includes a small inset map of the island of Taiwan on the left, with a dot indicating the rock's location. The main map shows a trail starting from a black dot at the top left and extending diagonally down to the right. A scale bar at the bottom indicates 0 to 3 meters. A north arrow is located at the bottom left.	 A dark, grainy digital photograph of the Agnes rock, showing its irregular shape and texture.

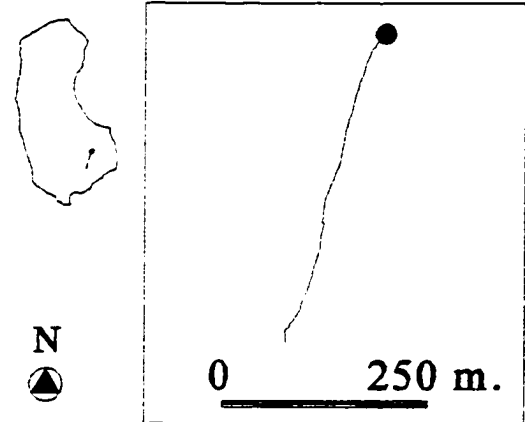
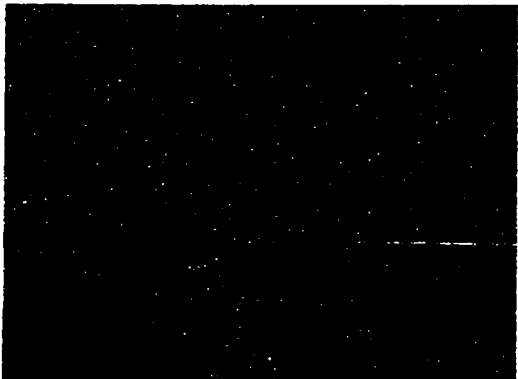
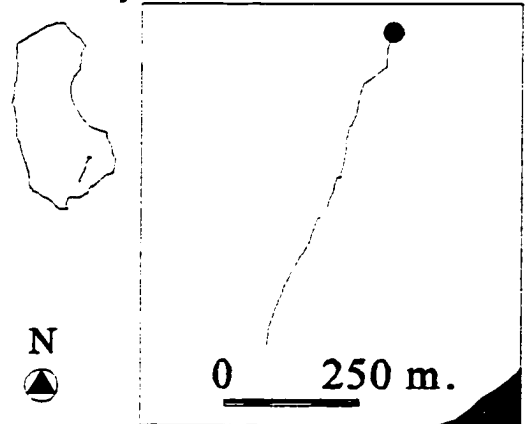
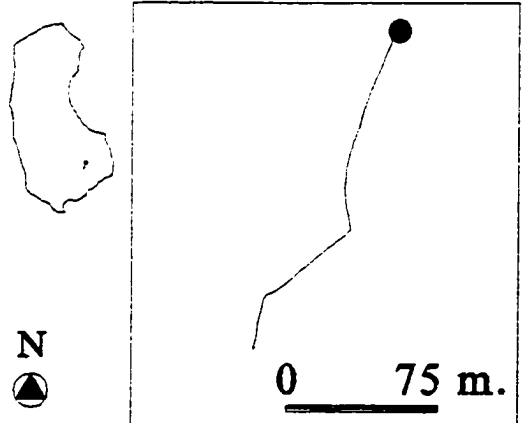
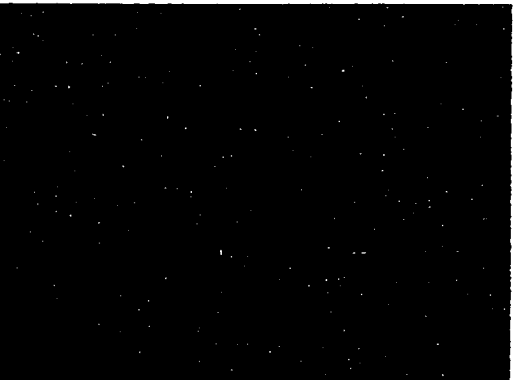
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
140 Debbie  The map for rock 140 Debbie shows a trail starting from a black dot at the top left, extending horizontally to the right, then turning down and slightly left. A scale bar at the bottom indicates 0 to 100 m. A north arrow is located to the left of the map.	 A dark, grainy digital image of rock 140 Debbie, showing a dark, irregularly shaped rock surface.
141 April  The map for rock 141 April shows a trail starting from a black dot at the top right, extending vertically down, then turning left. A scale bar at the bottom indicates 0 to 60 m. A north arrow is located to the left of the map.	 A dark, grainy digital image of rock 141 April, showing a dark, irregularly shaped rock surface.
142 Cindy  The map for rock 142 Cindy shows a trail starting from a black dot at the top right, extending vertically down. A scale bar at the bottom indicates 0 to 30 m. A north arrow is located to the left of the map.	 A dark, grainy digital image of rock 142 Cindy, showing a dark, irregularly shaped rock surface.

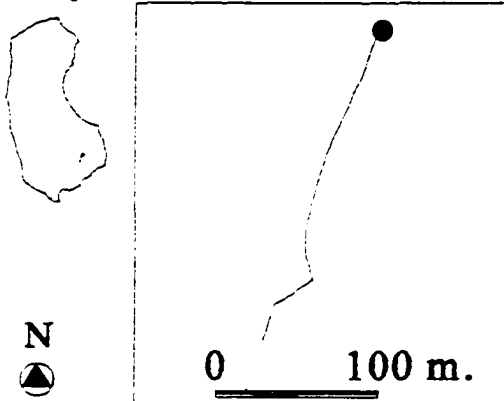
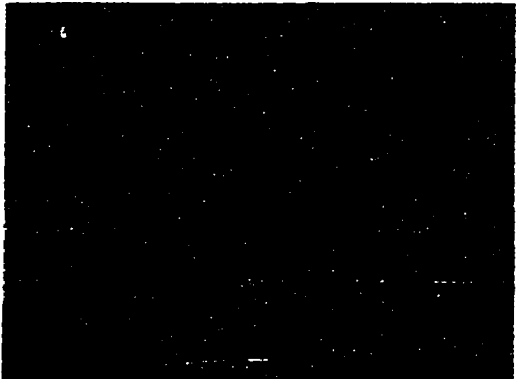
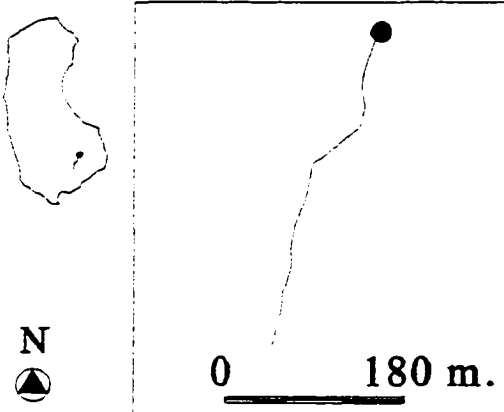
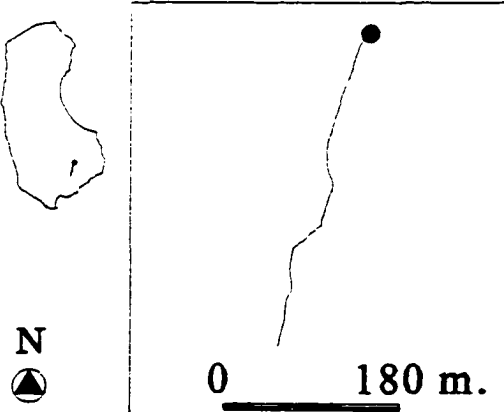
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
143 Betsy  The map for Betsy rock shows a trail starting from the bottom right and ending at a black dot representing the rock. A scale bar indicates 0 to 500 meters. A north arrow is located to the left of the map. An inset map of the island is shown to the left of the main map.	 A dark, grainy digital image of Betsy rock, showing a horizontal line across the middle.
144 Milly  The map for Milly rock shows a trail starting from the bottom right and ending at a black dot representing the rock. A scale bar indicates 0 to 500 meters. A north arrow is located to the left of the map. An inset map of the island is shown to the left of the main map.	 A dark, grainy digital image of Milly rock, showing a horizontal line across the middle.
145 Diane  The map for Diane rock shows a trail starting from the bottom right and ending at a black dot representing the rock. A scale bar indicates 0 to 600 meters. A north arrow is located to the left of the map. An inset map of the island is shown to the left of the main map.	 A dark, grainy digital image of Diane rock, showing a horizontal line across the middle.

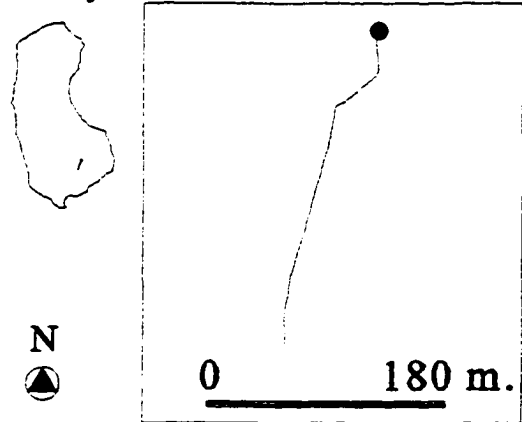
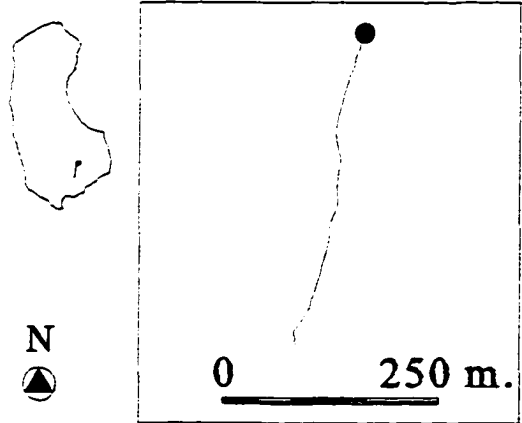
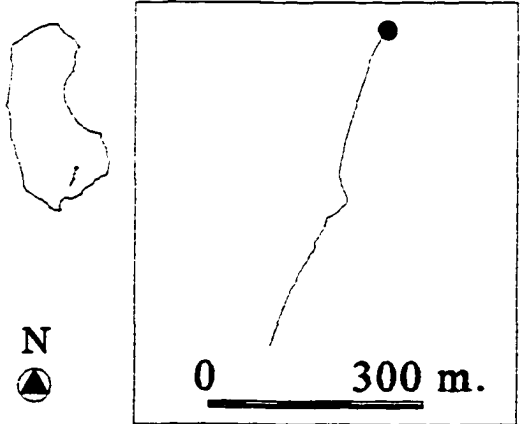
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
146 Dion  The map for rock 146 Dion includes a small inset map of the island of Tahiti with a dot indicating the rock's location. The main map shows a trail starting from the bottom left and ending at a black dot representing the rock. A scale bar at the bottom indicates 0 to 250 meters. A north arrow is located at the bottom left of the main map.	 A dark, grainy digital photograph of rock 146 Dion, which appears as a dark, irregularly shaped rock against a lighter background.
147 Kristy  The map for rock 147 Kristy includes a small inset map of the island of Tahiti with a dot indicating the rock's location. The main map shows a trail starting from the bottom left and ending at a black dot representing the rock. A scale bar at the bottom indicates 0 to 250 meters. A north arrow is located at the bottom left of the main map.	 A dark, grainy digital photograph of rock 147 Kristy, which appears as a dark, irregularly shaped rock against a lighter background.
148 Bonnie  The map for rock 148 Bonnie includes a small inset map of the island of Tahiti with a dot indicating the rock's location. The main map shows a trail starting from the bottom left and ending at a black dot representing the rock. A scale bar at the bottom indicates 0 to 75 meters. A north arrow is located at the bottom left of the main map.	 A dark, grainy digital photograph of rock 148 Bonnie, which appears as a dark, irregularly shaped rock against a lighter background.

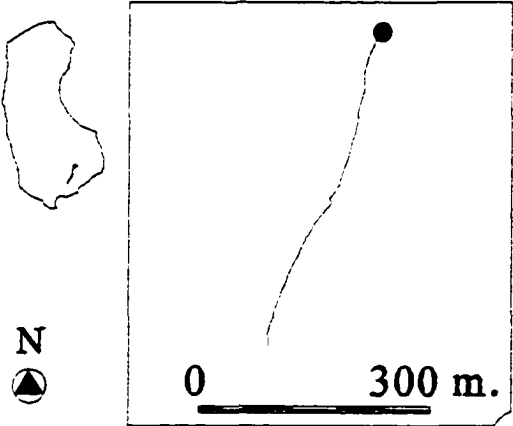
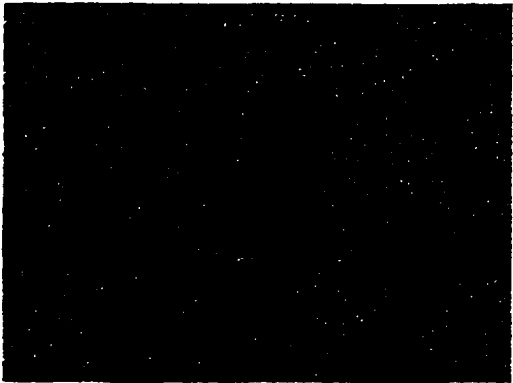
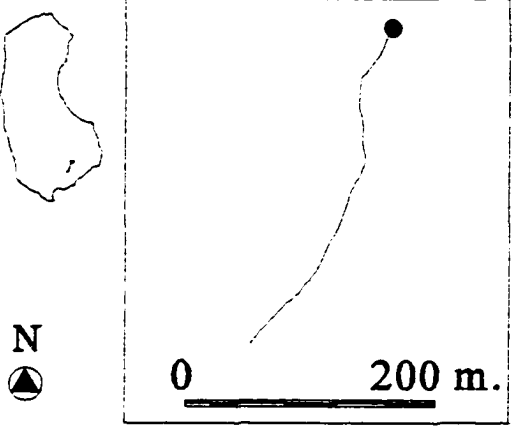
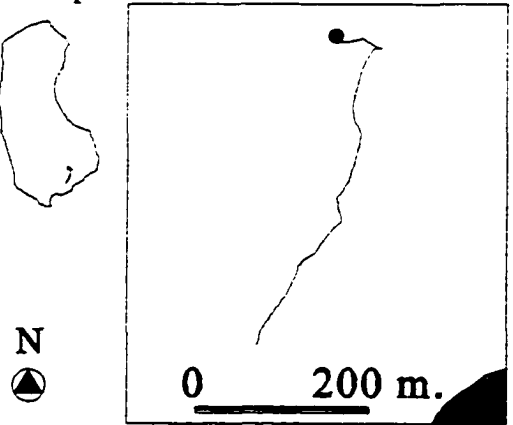
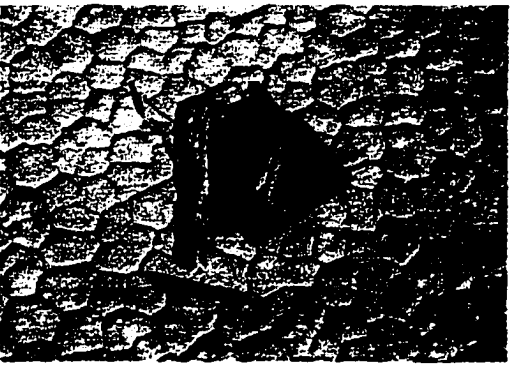
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
150 Ryan 	
151 Allison 	
152 Carmen 	

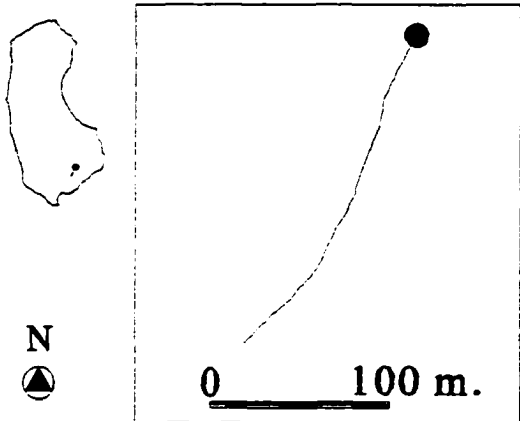
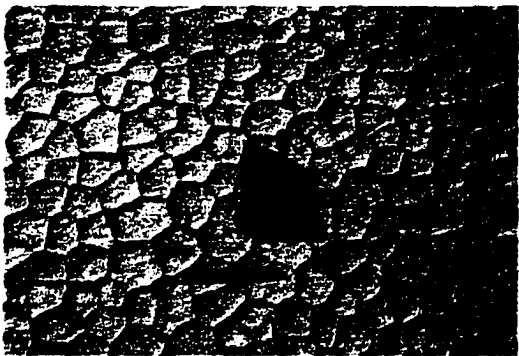
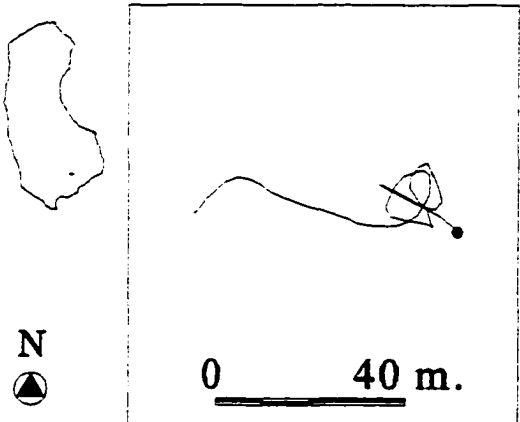
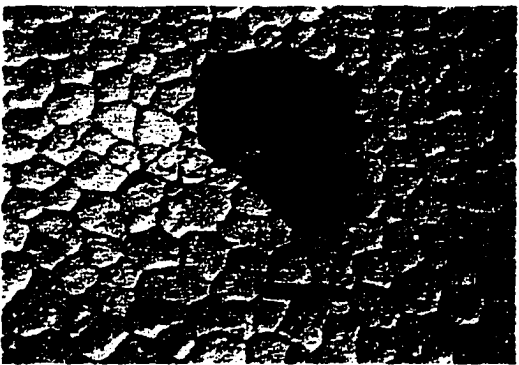
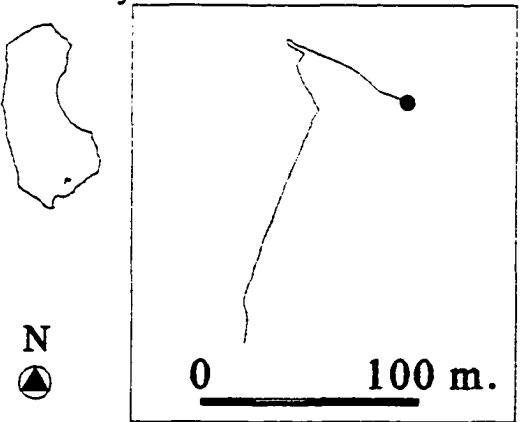
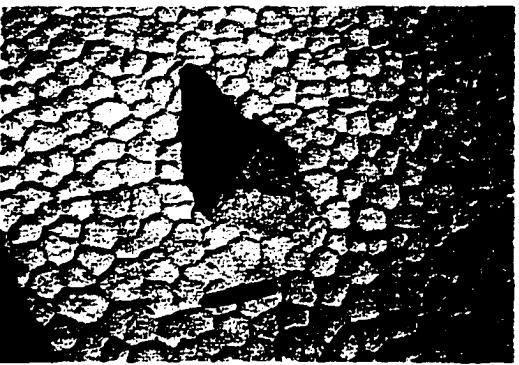
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
153 Layla  The map for rock 153 Layla includes a small inset map of the island of Ireland with a dot indicating the rock's location. The main map shows a trail starting from the bottom left and ending at a black dot representing the rock. A scale bar at the bottom indicates a distance of 180 meters. A north arrow is located in the bottom left corner of the map area.	
154 Marion  The map for rock 154 Marion includes a small inset map of the island of Ireland with a dot indicating the rock's location. The main map shows a trail starting from the bottom left and ending at a black dot representing the rock. A scale bar at the bottom indicates a distance of 250 meters. A north arrow is located in the bottom left corner of the map area.	
155 Aileen  The map for rock 155 Aileen includes a small inset map of the island of Ireland with a dot indicating the rock's location. The main map shows a trail starting from the bottom left and ending at a black dot representing the rock. A scale bar at the bottom indicates a distance of 300 meters. A north arrow is located in the bottom left corner of the map area.	

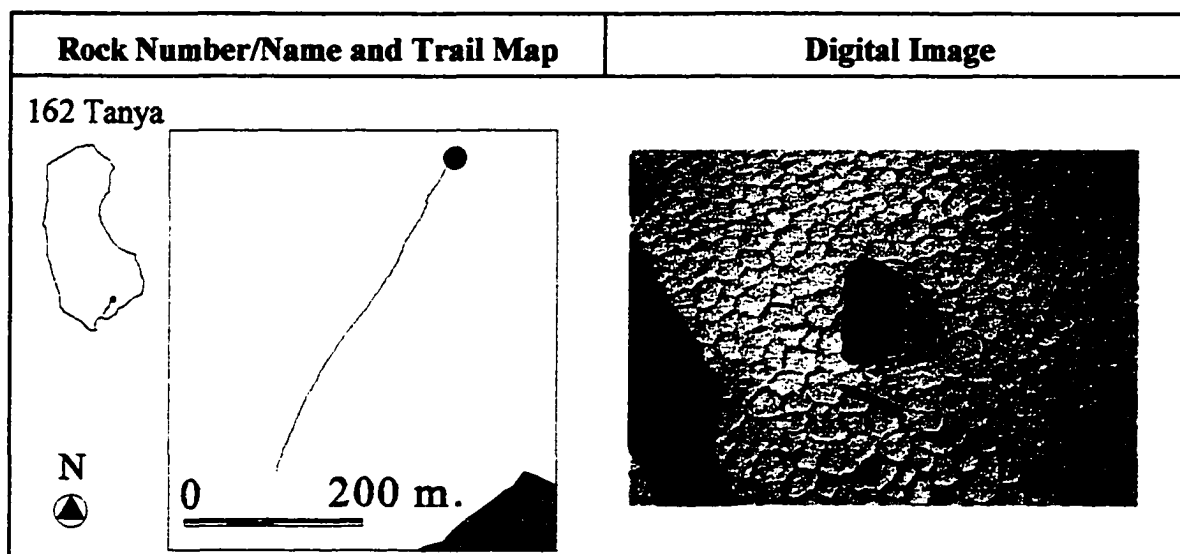
Maps are oriented with north at the top; images include a 10-centimeter ruled staff for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
156 Ruth  The map for Ruth rock shows a trail starting from the bottom left and ending at a black dot at the top right. A north arrow is located at the bottom left of the map area, pointing upwards. A scale bar at the bottom indicates 0 to 300 meters.	 A dark, grainy digital image of the Ruth rock, which is mostly black with some white speckles.
157 Alanis  The map for Alanis rock shows a trail starting from the bottom left and ending at a black dot at the top right. A north arrow is located at the bottom left of the map area, pointing upwards. A scale bar at the bottom indicates 0 to 200 meters.	 A dark, grainy digital image of the Alanis rock, which is mostly black with some white speckles.
158 Sophie  The map for Sophie rock shows a trail starting from the bottom left and ending at a black dot at the top right. A north arrow is located at the bottom left of the map area, pointing upwards. A scale bar at the bottom indicates 0 to 200 meters.	 A digital image of the Sophie rock, showing a textured, light-colored surface with a dark, rectangular feature in the center.

Maps are oriented with north at the top; images include a 10-centimeter ruled staff (#156 and #157) or 14-centimeter pen (#158) for scale, and are oriented with north to the left.

Rock Number/Name and Trail Map	Digital Image
159 June  The map for June 159 includes a small inset map of the study area with a dot indicating the location. The main map shows a trail starting from the bottom left and ending at a black dot in the top right. A scale bar at the bottom indicates 0 to 100 meters. A north arrow is located at the bottom left of the main map.	 A black and white photograph of a rock surface with a scale bar. The rock has a rough, textured surface with a dark, irregularly shaped feature in the center. A scale bar is visible at the bottom of the image.
160 Helen  The map for Helen 160 includes a small inset map of the study area with a dot indicating the location. The main map shows a trail starting from the bottom left, curving to the right, and ending at a black dot. A scale bar at the bottom indicates 0 to 40 meters. A north arrow is located at the bottom left of the main map.	 A black and white photograph of a rock surface with a scale bar. The rock has a rough, textured surface with a dark, irregularly shaped feature in the center. A scale bar is visible at the bottom of the image.
161 Hillary  The map for Hillary 161 includes a small inset map of the study area with a dot indicating the location. The main map shows a trail starting from the bottom left, curving to the right, and ending at a black dot. A scale bar at the bottom indicates 0 to 100 meters. A north arrow is located at the bottom left of the main map.	 A black and white photograph of a rock surface with a scale bar. The rock has a rough, textured surface with a dark, irregularly shaped feature in the center. A scale bar is visible at the bottom of the image.

Maps are oriented with north at the top; images include a 14-centimeter pen for scale, and are oriented with north to the left.



Map is oriented with north at the top; image includes a 14-centimeter pen for scale, and is oriented with north to the left.

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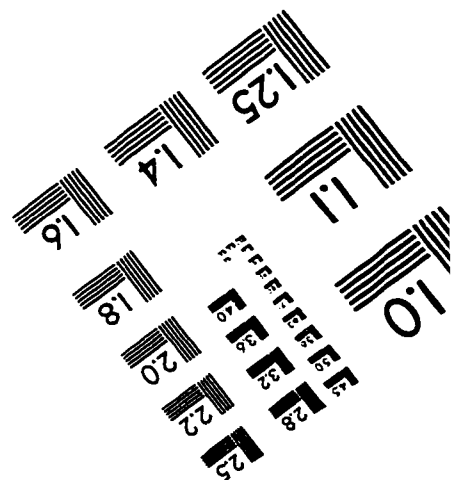
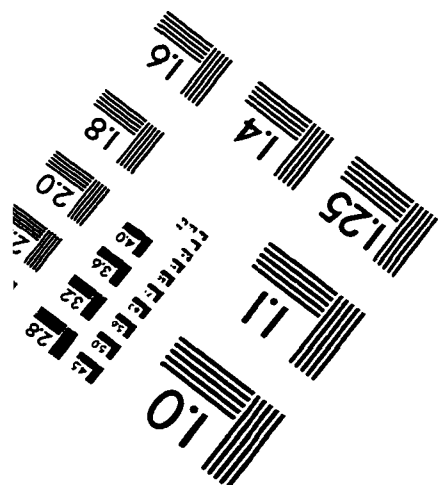
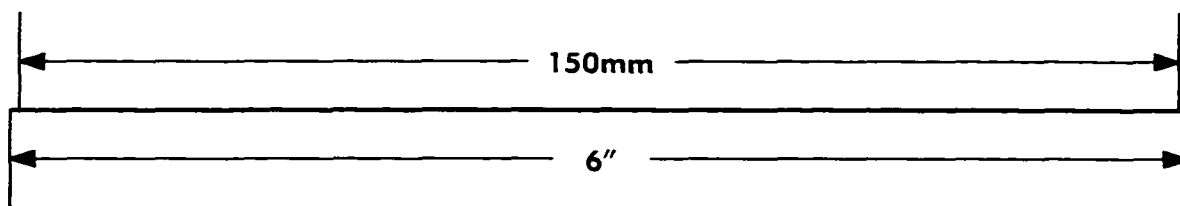
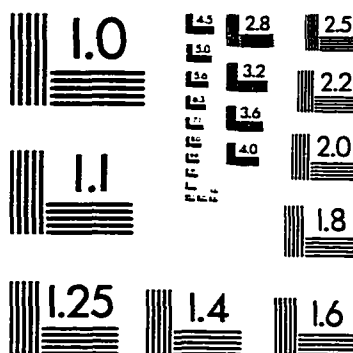
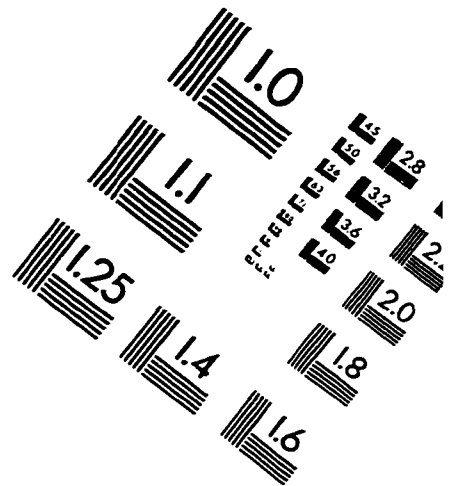
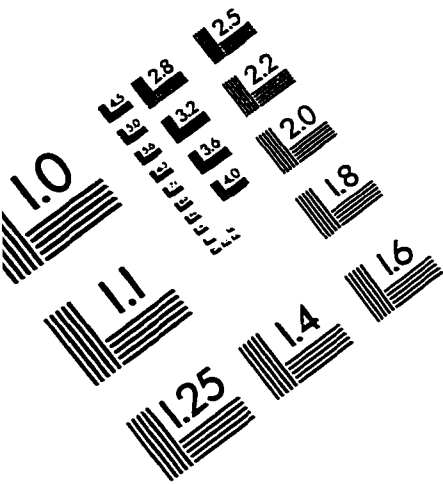
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IMAGE EVALUATION TEST TARGET (QA-3)



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