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Fifty-four years of ephemeral channel response to two years of intense World War II military activity, Camp Iron Mountain, Mojave Desert, California

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ABSTRACT

During World War II, U.S. Army personnel lived, trained, and executed mock battles on low gradient piedmonts (~2°) in the Mojave Desert. For example, Camp Iron Mountain (established in 1942 by General George S. Patton, Jr., and used until 1944) housed up to 20 000 Army personnel at any specific time. The camp is located on the large alluvial piedmont that extends from the Iron Mountains and is drained by shallow ephemeral channels.

At this camp, we made 18 detailed topographic maps in order to compare drainage networks of six undisturbed control plots and 12 plots disturbed by army activities. There are significant differences between the morphometery of small-scale, ephemeral drainage networks on control plots, on plots bisected by stone-walled walkways, and on plots down gradient of former army roads. Control plot channels are wider (2.05 ± 1.48 m) and deeper (8.8 ± 4.5 cm) than channels in walkway plots (width: 1.19 ± 0.71 m, depth: 7.4 ± 4.1 cm) and in road plots (width: 1.18 ± 0.61 m, depth: 7.2 ± 6.7 cm).

The military's modification of the landscape affected subsequent channel originations and orientations. Channel heads were found in 76% of the compacted and smoothed walkways. In walkway plots, 80% of walkways caused the orientation of channels to deviate from the steepest piedmont gradient by more than 20°. After more than 50 years, road berms still act as local drainage divides. Down gradient of each intact road berm, there is a wide (20–40 m) zone in which no channels exist. Where channels have developed below intact road berms, they are smaller than channels in undisturbed control plots. Down gradient of breached road berms, wide, braided channels are common. Fifty-four years after camp abandonment, the channel network at Camp Iron Mountain has yet to recover, primarily because rock alignments and road berms continue to influence drainage patterns and local gradients.

INTRODUCTION

A significant amount of military training is done in arid regions where rates of surface processes are slow and surface change is often episodic and thus difficult to observe and quantify. The U.S. military, as a steward of large tracts of land, is required by Army Regulation AR 200-2 to monitor the environmental effects of training exercises in arid regions (Prose, 1985). In order to place in perspective the effect of military maneuvers on the desert environment, one must understand

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rates of geomorphic processes and the rate at which natural systems recover from disturbance. Because many desert processes are so slow, results of short-term monitoring are often inconclusive (Abrahams et al., 1984). A longer-term perspective may be gained by studying areas where military activity occurred over a known and discrete time frame. Such data may allow identification and implementation of training protocols that minimize environmental impact.

From 1942 to 1944, the U.S. Army established twelve temporary base camps and living quarters in the Desert Training Center (Fig. 1A). Camp Iron Mountain (~ 6 km^2) was built on a low-gradient piedmont surface extending > 10 km from the Iron Mountains to Danby Lake playa in the Mojave Desert (Fig. 1B). At this camp, the Army constructed an extensive (4 km by 1.5 km) grid of roads (Fig. 1C). During road construction, berms (30–40 cm high) were built on both sides of each road. Troops outlined walkways, tents, and roads with angular granitic clasts ranging in size from 10 to 20 cm (Fig. 2). After two years of continuous use, the Army dismantled the camps in May 1944 (Henley, 1989). Today, the only evidence of occupation is the presence of road berms, rock alignments, rock designs, and other artifacts, in various states of deterioration.

The Iron Mountains are Cretaceous granite (Miller et al., 1981). The piedmont meets the mountain front at a sharp angle and is dominated by granular granitic alluvium (grus); median grain size is 2 mm. The piedmont slopes uniformly ~2° to the east where Camp Iron Mountain is located (Fig. 1B). Shallow, 10-cm deep ephemeral channels form gentle channel-terrace topography and dissect the surface.

The Iron Mountain piedmont receives an average of 7.9 cm of precipitation a year (National Oceanic and Atmospheric Administration, 1982). Late summer thunderstorms and mid-winter cyclonic events produce the majority of precipitation. Most precipitation infiltrates the grus. Runoff occurs only during rare, high-intensity rainfall events. Iverson et al. (1981) determined that runoff events in the western Mojave Desert probably occur about once per decade in undisturbed areas and more frequently in disturbed areas. As overland flow moves down the piedmont, some of the flow infiltrates the unsaturated grus (Bull, 1991; Ritter, 1978).

In areas where no channels exist, sheetwash is the dominant overland flow mechanism (Horton, 1945). Sheetwash continues until flow depth is great enough so that: (1) a critical basal shear stress is reached and channel incision begins (Horton, 1945; Montgomery and Dietrich, 1994), or (2) raindrops cannot obliterate incipient channels as they begin to concentrate flow (Dunne, 1980). Small channels then form and transport sediment until the sediment load becomes greater than the transport capacity. When deposition occurs, caused by flow loss (infiltration) or a decrease in local gradient, many of the small channels diffuse into the planar surface. Such discontinuous channel morphologies dominate inside Camp Iron Mountain.

Historic photographs document that constant foot, vehicle, and tank traffic destroyed most, if not all, of the small channels during the occupation of Camp Iron Mountain (Fig. 2). Thus, we can reasonably assume a surface absent of channels inside the camp when our experiment began in May 1944. We assume that road berms and rock alignments were intact at the time of evacuation. Because the area is remote and the nearest populated town is more than 55 km away (Desert Center, California, population 120), post-army activity is limited to natural processes (overland flow and bioturbation) and occasional off-road vehicle (ORV) use. Around 1980, a fence was constructed around Camp Iron Mountain that stopped all ORV traffic (Bureau of Land Management, 1986).

Camp Iron Mountain provides a unique opportunity to investigate the redevelopment of an ephemeral channel network after two years of intense military training. We collected data 54 years after camp abandonment, in May 1998. In this chapter, we use our observations and data, in conjunction with previous research illustrating that human influence increases soil density (Prose, 1985; Webb et al., 1986), soil compaction, and soil surface smoothness (Iverson, 1980; Iverson et al., 1981), to develop a process model of channel response to military activity on low-gradient arid landscapes.

METHODS

In order to determine whether environmental impacts persisted half a century after the U.S. Army abandoned Camp Iron Mountain, we compared ephemeral channel depths, widths, areas, orientations, and drainage densities in three types of experimental plots (60 m by 60 m square areas). *Control plots* are representative of undisturbed conditions and are outside Camp Iron Mountain. *Walkway plots* contain rock alignments and are representative of disturbed conditions inside the camp. *Road plots* contain road berms at the up-gradient boundary and are also representative of disturbed conditions inside the camp. By comparing data gathered from these different types of plots, we determine the degree to which past military activities still affect the desert surface, in particular, the geometry of ephemeral channels that drain the Iron Mountain piedmont.

Survey methods

We outlined plot boundaries by using a Pentax PCS-2 total station to delineate 60 m orthogonal sides on all plots except Control Plot 3, where we used a tape and compass survey. We used flags to outline all channels within plot boundaries. Each plot was surveyed using a Trimble 4400 real time kinematic differential Global Positioning System (GPS), precise to within several centimeters horizontally and ~1 cm vertically. We surveyed topography using a five-meter grid spacing and surveyed each channel by making a series of cross sections, with the exception of Control Plot 3 and Road Plot 1, where cross sections were not measured. Each cross section consisted of two bank-top points, two bank-bottom points, and any points of significant topographical change within the channel. In places

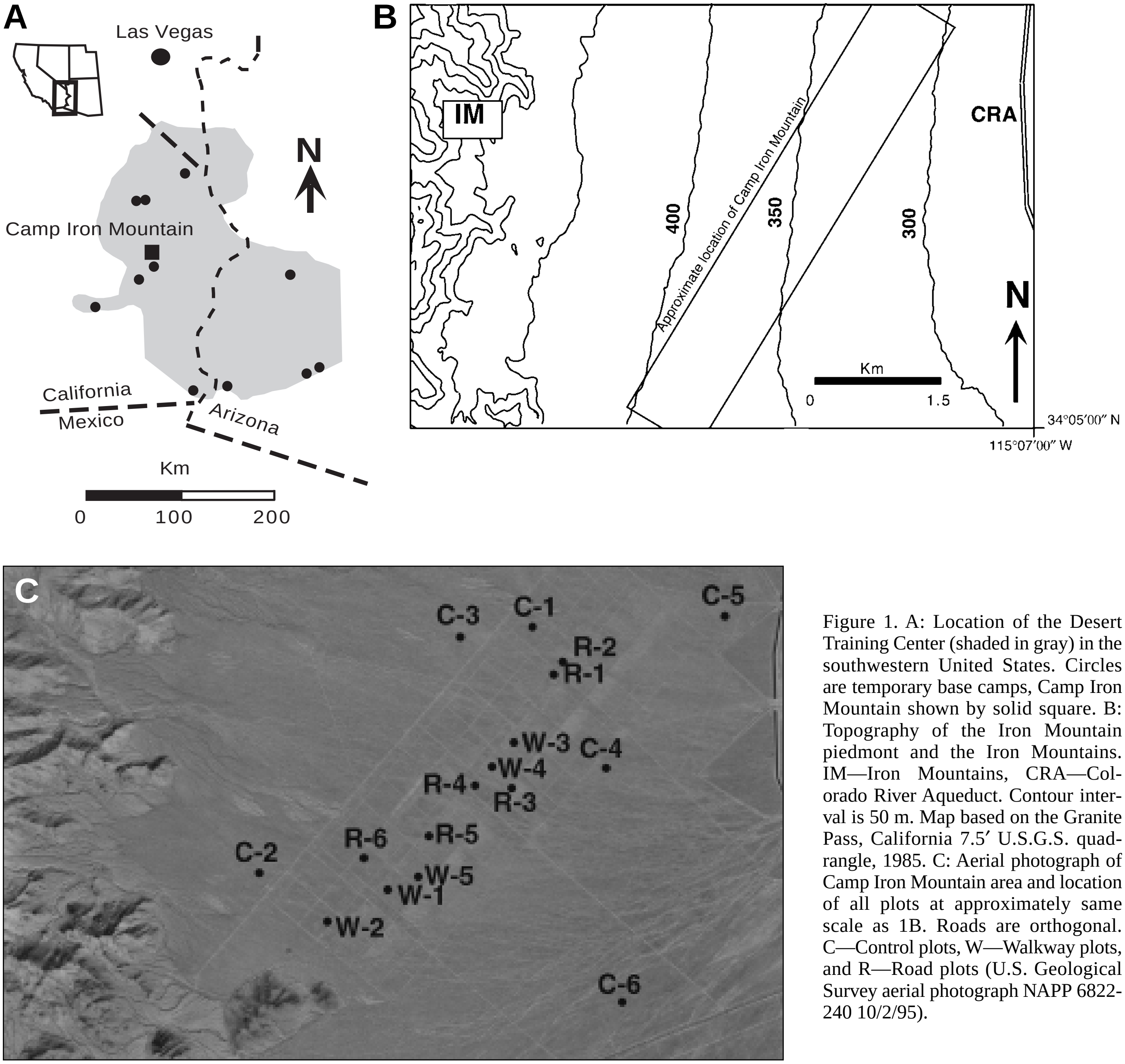


Figure 1. A: Location of the Desert Training Center (shaded in gray) in the southwestern United States. Circles are temporary base camps, Camp Iron Mountain shown by solid square. B: Topography of the Iron Mountain piedmont and the Iron Mountains. IM—Iron Mountains, CRA—Colorado River Aqueduct. Contour interval is 50 m. Map based on the Granite Pass, California 7.5′ U.S.G.S. quadrangle, 1985. C: Aerial photograph of Camp Iron Mountain area and location of all plots at approximately same scale as 1B. Roads are orthogonal. C—Control plots, W—Walkway plots, and R—Road plots (U.S. Geological Survey aerial photograph NAPP 6822-240 10/2/95).

where channel banks could not be defined, the channel margins were labeled as wash banks. In walkway plots, we also surveyed all rock alignments. For each plot, an average of 454 topographic data points was collected.

After surveying each plot, we contoured the data at ten-centimeter intervals. Before removing the channel boundary flags, we field-checked maps of each plot to verify the accuracy of channel locations. We made observations of characteristics, inside and outside each plot, that influence channel morphology. We made a photographic record of each plot, and noted photograph locations and orientations on each map.

Plot locations

We randomized the selection of all plot locations within characteristic areas. Control plots were located outside Camp Iron Mountain. Walkway plots were inside the camp and contained visible rock alignments and no roads. We chose walkway plot locations by walking inside the camp until we could see rock alignments extending approximately 80 m in all directions. To minimize bias, we walked 20 additional steps, in the same direction, before setting up the plot boundaries. All road plots contained a road berm that formed the up-gradient boundary. Road

Figure 2. Photograph of Camp Iron Mountain after a sandstorm. Rock alignments are visible in front of tents. After camp abandonment, rock alignments were left intact. Foot and vehicle traffic has obliterated ephemeral channel network. National Archives photo #111-SC-145201.

plots did not contain roads or rock alignments, except for one plot that contained a 10-m rock alignment. We chose the road plots by walking along a road until we could not see rock alignments for at least 60 m.

Data reduction

We used cross section data to calculate channel depths, widths, and channel cross-sectional areas. Channel depths are defined as bank-bottom elevations subtracted from bank-top elevations. We used the GPS northing (N) and easting (E) coordinates and the following equation to define the channel widths:

$$W = [(E_L - E_R)^2 + (N_L - N_R)^2]^{1/2} \tag{1}$$

where W is the width, E_L is left bank easting coordinate, E_R is right bank easting coordinate, N_L is left bank northing coordinate, and N_R is right bank northing coordinate. Cross-sectional areas are defined as the channel width multiplied by the average channel depth.

We used our high-resolution topographic maps to determine channel surface areas, drainage densities, and channel orientations. We digitized each map to calculate the total area of each plot occupied by channels. Drainage densities for plots are defined as the sum of channel lengths divided by the plot area (Dunne and Leopold, 1978). The drainage densities for channels inside old walkways (inside the walkway plots) are defined as the sum of channel lengths inside old walkways divided by the old walkway area. Since most channels in the plots are linear, we determined channel orientation by measuring each representative channel orientation with respect to north. For channels with curvature, we measured the average direction of flow determined by connecting the upstream end of the channel to the downstream end of the channel.

RESULTS

Visual observations made at Camp Iron Mountain imply that human influences on the surface morphology persist 54 years after the camps were abandoned. Detailed topographic mapping shows differences in channel characteristics between control and experimental plots. The data support visual observations that ephemeral channel networks have not recovered to background conditions more than a half-century after Army abandonment.

Depth, width, and cross-sectional area data

On average, control plot channels are significantly deeper (99.9% confidence level) than walkway (t = 6.27, df = 1396, $P < 0.001$) and road (t = 7.63, df = 1397, $P < 0.001$) plot channels, and have an average depth of 8.9 ± 4.5 cm (n = 756), where t is the statistic, df is the degrees of freedom, P is the probability value, and n is the sample population. Average channel depths in walkway and road plots are 7.4 ± 4.1 cm (n = 647) and 7.2 ± 6.7 cm (n = 653), respectively (Table 1). Channel depths in walkway and road plots are not statistically different ($t = 0.65$ $df = 1272$, $P > 0.52$). Data for all plots are right skewed (Fig. 3).

Channels in control plots are significantly wider (99.9% confidence level) than channels in walkway ($t = 9.29$, $df = 428$, $P < 0.001$) and road ($t = 8.53$, $df = 531$, $P < 0.001$) plots. Control plot channel widths average 2.05 ± 1.48 m ($n = 319$). Average channel widths for walkway and road plots are 1.19 ± 0.71 m ($n = 418$) and 1.18 ± 0.61 m ($n = 224$), respectively (Table 2). Widths of channels in walkway and road plots are not statistically different ($t = 0.58$, $df = 372$, $P > 0.56$). Control plot channels have a greater range in widths compared to widths in disturbed plots. Data are skewed to the right for all plots (Fig. 3).

Control plot channels have, on average, statistically larger cross-sectional areas than walkway ($t = 8.01$, $df = 409$, $P < 0.001$) and road ($t = 11.04$, $df = 385$, $P < 0.001$) plot channels (Table 3). The average cross-sectional area for control plot channels is 0.157 ± 0.039 m^2 ($n = 288$). The average cross-sectional areas for walkway and road plot channels are 0.077 ± 0.031 m^2 ($n = 331$) and 0.086 ± 0.060 m^2 ($n = 198$), respectively. Road plot channels have statistically larger cross-sectional areas than walkway plot channels ($t = 5.01$, $df = 449$, $P < 0.001$).

Channel area and drainage density

Control plots channel areas are statistically larger than walkway channel areas at the 90% confidence level ($t = 2.07$, $df = 9$, $P < 0.1$), and road channel areas at the 70% confidence level ($t = 1.26$, $df = 9$, $P < 0.3$). Channels in control plots cover an average of 733 ± 297 m^2, 20% of the average control plot area. Walkway plot channels cover an average of 432 ± 199 m^2, 12% of the average walkway plot area. The average road plot channel area is 490 ± 367 m^2, 14% of the average road plot area (Table 4). Walkway and road plot channel areas are not statistically different ($t = -0.34$, $df = 9$, $P > 0.5$).

Control plot drainage densities are not statistically different than walkway plot drainage densities ($t = 0.68$, $df = 9$, $P > 0.5$). The average drainage density for control plots is 0.096 ± 0.036 m/m^2, while walkway plots have an average drainage density of 0.084 ± 0.027 m/m^2. Road plots have an average drainage density of 0.067 ± 0.023 m/m^2 (Table 5). Road plot drainage densities are statistically smaller than control plot drainage densities at the 80% confidence level ($t = 1.71$, $df = 9$, $P < 0.2$) and walkway plot drainage densities at the 70% confidence level ($t = 1.19$, $df = 10$, $P < 0.3$).

Channel orientations

Channels are usually oriented down the Iron Mountain piedmont's steepest gradient, 103 ± 16° based on a plot-by-plot analysis of our topographic maps. Walkway plot channel orientations are bimodal (Fig. 4). In fact, more channels in walkway plots have the same orientation as walkways (126°) than have the orientation of the average steepest gradient (103°). Control plot channels exhibit the largest range of orientations (101 ± 20°), but control plots are more widely distributed across the piedmont surface than walkway and road plots (Fig. 1C). Road plot channels have the smallest range of orientations (103 ± 11°), following the steepest piedmont gradient and consistent with the smooth surface topography below the intact road berms.

TABLE 1. CHANNEL DEPTHS FOR CONTROL, WALKWAY, AND ROAD PLOTS

Plot	Control (cm)	Walkway (cm)	Road (cm)
1	10.7 ± 5.4 (126)	6.5 ± 2.8 (100)	9.0 ± 4.0 (222)
2	7.4 ± 2.5 (59)	8.4 ± 4.1 (125)	6.1 ± 2.9 (127)
3	9.9 ± 5.0 (178)	5.5 ± 2.5 (80)	5.8 ± 2.5 (77)
4	7.9 ± 3.9 (155)	7.1 ± 4.4 (120)	7.6 ± 2.9 (69)
5	8.2 ± 4.1 (142)	6.1 ± 3.0 (61)	5.1 ± 2.4 (86)
6	8.1 ± 4.1 (96)	8.8 ± 4.8 (161)	7.7 ± 3.5 (72)
Average of all channels	8.9 ± 4.5 (756)	7.4 ± 4.1 (647)	7.2 ± 6.7 (653)

Note: Average and standard deviations are determined using *n* values in parenthesis. Paired depths for channel cross sections are assumed to be independent observations because left and right banks are poorly correlated ($r^2 = 0.05$).

DISCUSSION

Camp Iron Mountain has been recovering from a discrete environmental impact for the past 54 years. Our data for ephemeral channels show that recovery is far from complete. There remain measurable and distinct differences between channel characteristics in control and experimental plots. The differences are primarily due to the presence of rock alignments, road berms, and the smoothing and compaction of the surface. By diverting shallow overland flow and changing surface roughness, human activity has altered surface water flow patterns within the camp as indicated by measurements made in the experimental plots. Our data support the conclusions of Iverson (1980) that ORV use, or in this study, military activity, reduces infiltration and changes the roughness of desert surfaces.

Control plots

Control plots are representative of undisturbed conditions on the Iron Mountain piedmont. Control plots are located both upslope and downslope of Camp Iron Mountain. The average channel depths, channel widths, channel areas, channel orientations, and drainage densities are similar for all control plots (Tables 1, 2, 3, 4, and 5).

On average, control plot channels are almost a meter wider and are more continuous than walkway and road plot channels, thus providing for greater channel areas and drainage densities (Tables 4 and 5). Control plot channels are on average 1.5 cm deeper than average walkway and road plot channels (Table 1). Average channel orientations deviate little (101 ± 20°) even though control plot six is located at the convergence of the Iron Mountain and Granite Mountain piedmonts. The internal consistency of the control plot data, despite the distance between plots (up to 3 km),

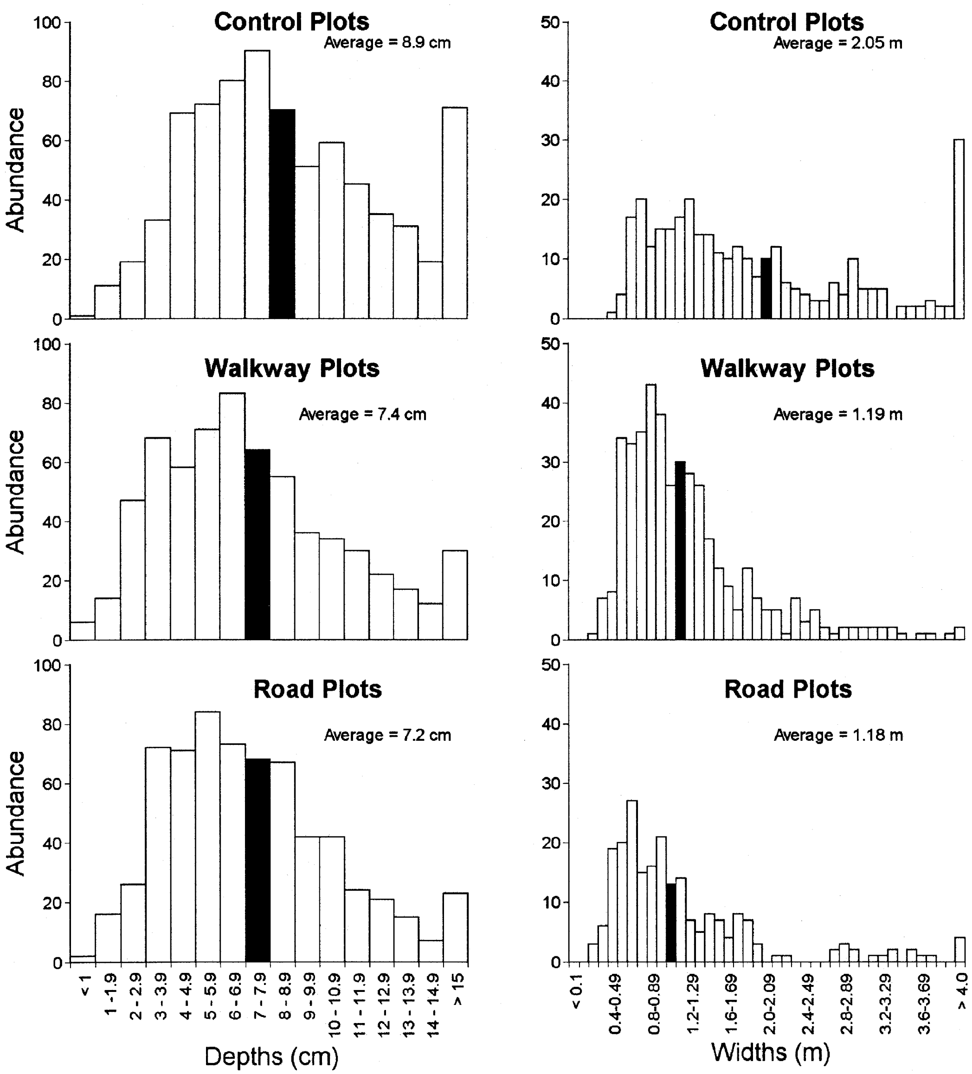


Figure 3. Distribution of channel depths and widths for control, walkway, and road plots. The black bar represents mean value.

TABLE 2. CHANNEL WIDTHS FOR CONTROL, WALKWAY, AND ROAD PLOTS

Plot	Control (m)	Walkway	Road
1	2.42 ± 1.37 (75)	1.02 ± 0.63 (78)	N.D.*
2	2.02 ± 2.02 (34)	1.10 ± 0.45 (65)	1.15 ± 0.50 (50)
3	N.D.*	1.34 ± 0.97 (58)	0.88 ± 0.57 (41)
4	2.10 ± 1.27 (75)	1.43 ± 0.83 (57)	1.36 ± 0.52 (35)
5	1.94 ± 1.58 (69)	1.09 ± 0.50 (76)	0.63 ± 0.27 (59)
6	1.63 ± 1.31 (55)	1.40 ± 0.69 (84)	2.23 ± 1.44 (38)
Average of all channels	2.05 ± 1.48 (308)	1.19 ± 0.71 (418)	1.18 ± 0.61 (223)

Note: Average and standard deviations are determined using *n* values in parenthesis.

*N.D. = not determined

supports the observation that the Iron Mountain piedmont is a homogeneous planar surface experiencing similar ephemeral channel processes along its entire length and width (Fig. 5).

Walkway plots

Channel characteristics in walkway plots are influenced strongly by the combination of rock alignments and the compaction and smoothing of roughness elements caused by two years of foot traffic on the walkways. Up gradient of some walkway areas, there are discontinuous rock alignments that disperse overland flow and impede channel incision. Where channels have incised, rock alignments influence the orientation of flow. Eighty percent of all walkway rock alignments act as a barricade to flow and cause channel orientations to deviate at least 20° from the steepest gradient. Small channels that form in, or just up gradient of walkways, have orientations along the walkway (Fig. 6), until

TABLE 3. CHANNEL CROSS-SECTIONAL AREAS FOR CONTROL, WALKWAY, AND ROAD PLOTS

Plot	Control (m^2)	Walkway (m^2)	Road (m^2)
1	0.219 ± 0.143 (64)	0.046 ± 0.031 (55)	N.D.*
2	0.119 ± 0.105 (30)	0.095 ± 0.058 (65)	0.061 ± 0.047 (48)
3	N.D.*	0.052 ± 0.046 (39)	0.040 ± 0.025 (31)
4	0.040 ± 0.025 (31)	0.101 ± 0.098 (56)	0.106 ± 0.062 (35)
5	0.106 ± 0.062 (35)	0.046 ± 0.040 (40)	0.029 ± 0.022 (59)
6	0.115 ± 0.122 (52)	0.127 ± 0.089 (78)	0.193 ± 0.146 (35)
Average of all channels	0.157 ± 0.039 (288)	0.077 ± 0.031 (331)	0.086 ± 0.060 (198)

Note: Average and standard deviations are determined using *n* values in parenthesis.
*N.D. = not determined

TABLE 4. CHANNEL AREAS FOR CONTROL, WALKWAY, AND ROAD PLOTS

Plot	Control (m^2)	Walkway (m^2)	Road (m^2)
1	1064	287	1160
2	477	302	630
3	603	361	314
4	1100	547	258
5	765	307	152
6	394	787	427
Average	733 ± 297	432 ± 199	490 ± 367

Note: Average and standard deviation are determined using plot values.

TABLE 5. DRAINAGE DENSITIES FOR CONTROL, WALKWAY, AND ROAD PLOTS

Plot	Control (m/m^2)	Walkway (m/m^2)	Road (m/m^2)
1	0.123	0.071	0.100
2	0.052	0.068	0.091
3	0.068	0.056	0.052
4	0.138	0.097	0.049
5	0.124	0.078	0.045
6	0.073	0.132	0.061
Average	0.096 ± 0.036	0.084 ± 0.027	0.066 ± 0.023

Note: Average and standard deviation are determined using the plot values.

either the walkway ends, the flow has enough power to breach the rock alignment, or sediment load exceeds the transport capacity and the channels diffuse into the surface. Larger channels usually have flow directions controlled by overall topography, regardless of the presence of rock alignments (Fig. 7).

Interestingly, walkway plot channel areas are approximately half that of the control plot channel areas, while drainage densities are similar. Channel areas differ and drainage densities are similar because the more numerous, smaller, and discontinuous walkway channels (Fig. 7) have approximately the same total channel length as the less frequent, wider, and more continuous control plot channels (Fig. 5).

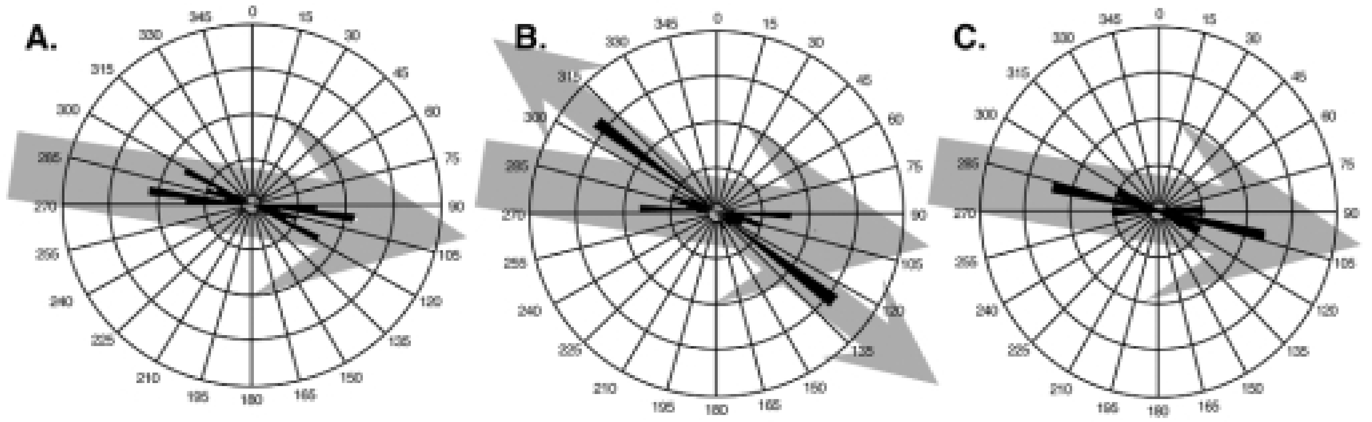
Compacting the soil and smoothing surface roughness elements aid in the incision of new channels (Iverson, 1980). Compaction decreases infiltration capacities (Hillel, 1980) and allows runoff at lower precipitation intensities and durations. Smooth surfaces generate greater flow velocities than rough surfaces, increasing basal shear stresses and promoting channel incision. Prose (1985) found that soils at Camp Iron Mountain were compacted enough after only one pass of a medium-sized tank to promote rill and gully formation within the tank tracks. The walkways experienced two years of foot traffic, which was effective in smoothing roughness elements and compacting the soil. Over 76% of walkways have channels that start within them, due presumably to decreased infiltration capacities and the smooth surface. Many of these channels dissipate further down gradient, but some channels extend beyond the plot boundaries.

Road plots

Most literature on the impact of roads on drainage networks centers on logging roads in mountainous regions. Logging roads cause increased erosion rates and landslide initiation (Montgomery, 1994), more peaked hydrographs (Wemple et al., 1996), and changes in channel morphology. We, however, are investigating the effects of temporary roads, established on a low-gradient surface in an arid environment. Our data do not suggest increased erosion rates, landslide initiation, or more peaked hydrographs, but do reveal changes in channel morphologies.

Channel characteristics of road plots are strongly influenced by the presence of paired road berms up gradient. Road berms act as local drainage divides, channeling and diverting overland flow. The paired berms around each road collect surface runoff and concentrate flow until either a crossroad of steeper gradient is encountered, or there is enough water to breach the berm and flow unconfined down the steepest gradient (Fig. 8). Intact road berms divert water away from some road plots. Down gradient of the intact road berms there is usually a zone (20 to 40 m) where shallow sheetflow must dominate and channels are absent (Fig. 9). Down gradient of a berm breach, the flow disperses and forms a braided channel (Fig. 10). The presence of wide, braided channels accounts for the larger average and standard deviation in cross-sectional area and channel area for road plots in comparison to the walkway plots (Tables 3 and 4). However, the relatively few channels in road plots (compared to walkway plots) account for a lower drainage density (Fig. 11).

Channel orientations in road plots are less variable than channel orientations in walkway and control plots (Fig. 4). The road plot channels have a uniform surface with few flow obstruc-



Control Plots **Walkway Plots** **Road Plots**

Figure 4. Rose diagrams of channel orientations. The light gray arrow represents the average orientation of the steepest topographic gradient for all plots. Each successive larger circle represents five channels with the same orientation. A: Control plots B: Walkway plots (smaller, double barbed arrow represents walkway orientation) C: Road plots.

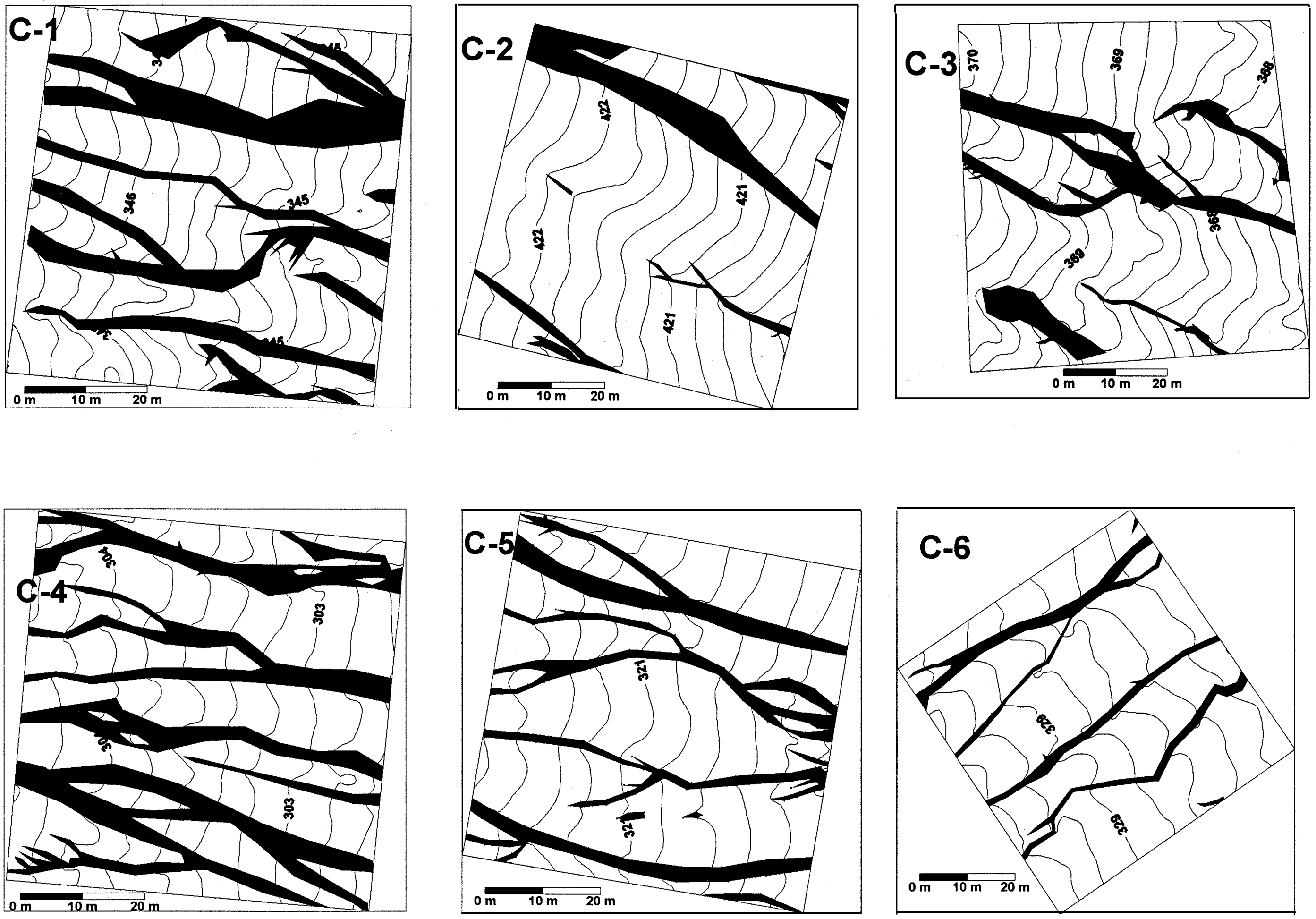


Figure 5. Maps of all control plots. Scale bar and direction are in C-6. Contour interval = 0.2 m. Elevations in maps are precise to ± 1 cm, but real elevations are ± 30 m, due to systematic GPS inaccuracy.

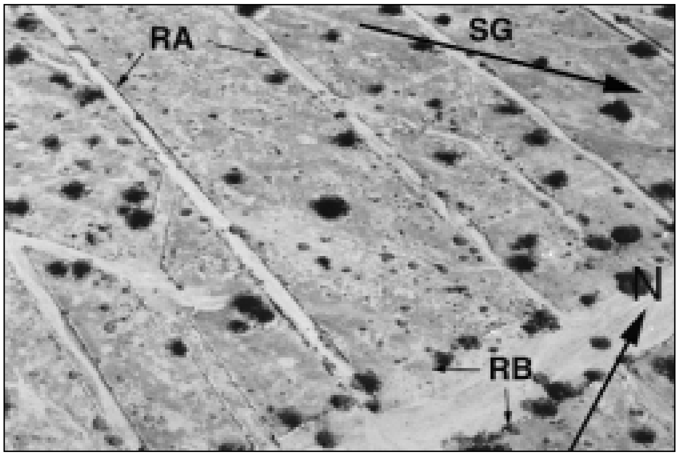


Figure 6. Low-level oblique aerial photograph of channels breaching walkway rock alignments at Camp Iron Mountain (from H. Wilshire). Arrows from RA point to rock alignments; RB point to road berms and SG point down steepest gradient. Walkways are ~1.5 m wide.

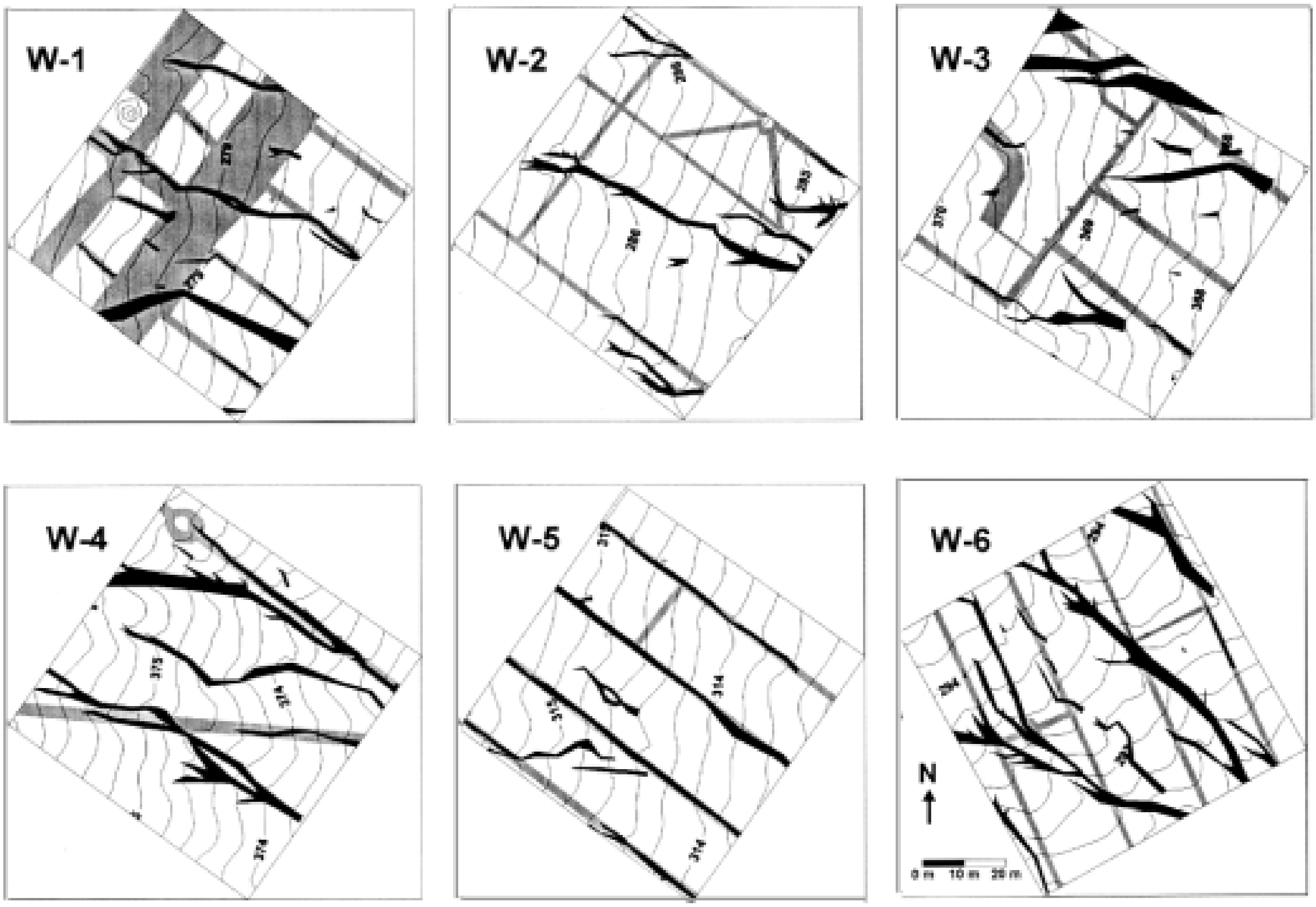


Figure 7. Maps of all walkway plots. Scale bar is in W-6. Contour interval = 0.2 m. Walkways are gray and channels are black. Elevations in maps are precise to ± 1 cm, but real elevations are ± 30 m, due to systematic GPS inaccuracy.

Figure 8. Low-level oblique aerial photograph of Camp Iron Mountain showing road berms channeling flow. Crossroads that are oriented down steeper gradients become wide washes. Roads are ~7 m wide. SG—Steepest gradient (from H. Wilshire).

tions. Most channels in road plots develop within the plots (Fig. 11), their orientation controlled directly by the steepest local gradient. The uniform surface, the closer spatial distribution of road plots when compared to the control plots, and the fact that most channels in road plots are developed within the plot account for the low variance in road plot channel orientations.

Process model

In order to generalize our results in a qualitative model, we must understand the surface processes affecting the Iron Mountain piedmont. Such a qualitative model must not only be consistent with our understanding of desert surface processes, but must also explain our observations at the camp and the observations of others (Iverson, 1980; Iverson et al., 1981; Prose, 1985; Webb et al., 1986). By understanding the dominant physical processes occurring on desert surfaces, we can suggest ways to minimize the impact of military training in arid regions.

Iverson (1980) concluded that ORV use in the western Mojave Desert compacted and smoothed microtopography, which led to hydraulic responses that increased soil erosion in disturbed areas. At Camp Iron Mountain, tanks, vehicles, and troops compacted and smoothed the soil (Prose, 1985). The compacted soil has fewer and smaller pores and thus lower infiltration rates. Reduced infiltration increases the volume and frequency of overland flow (Iverson et al., 1981). Troops and vehicles smoothed microtopography, which normally acts to disperse flow energy and cause localized sediment deposition. Iverson (1980) found a 13-fold decrease in surface roughness after just a few passes of an ORV. As a result of soil compaction and surface smoothing, overland flow volumes increase, along with the potential for channel incision, especially on heavily impacted areas such as walkways.

Walkways, the most compacted and smoothed features we mapped, have the highest frequency of channel heads (Santos, 1999). As argued above, this observation is consistent with soil compaction and surface smoothing. Iverson (1980) noted a strong positive correlation between runoff power and sediment yield ($r^2 = 0.78$) for desert surfaces. Increased sediment yield at Camp Iron Mountain is expressed by channel formation. The abundance of channel heads on walkways suggests that runoff power must be higher on walkways than elsewhere. Compacting and smoothing walkway surfaces decreased infiltration, increased local discharge, and thus increased runoff power.

Control plot channels are mostly continuous through the plots, have larger widths and depths, and thus larger channel cross-sectional areas than channels in disturbed plots. For alluvial rivers, larger channel cross-sectional areas correspond to larger drainage areas (Dunne and Leopold, 1978). However, the piedmont experiences overland flow and does not have clearly defined drainage divides, except for road berms. Unlike their larger cousins, individual widths and depths of piedmont channels do not change significantly or predictably as a function of distance from channel head (Fig. 12). Linear models of such relationships have low slopes, and channel widths and depths are poorly correlated with distance from the channel head. Thus, channel widths and depths change little as a function of channel length, and the size of the local drainage area does not control the size of the channels on the piedmont. Rather, the channels appear to attain a “steady state” size at which incoming overland flow and precipitation balance infiltration losses.

Low drainage densities of road plots are a direct result of intact road berms. Road berms collect runoff and divert water to intersections with roads that are sub-parallel to slope, thereby limiting overland flow in areas down gradient of intact berms. In these flow-deprived areas, sheetwash dominates for 20 to 40 m down gradient of the road berm, where there are few or no channels. This zone, absent of channels, lowers the drainage densities for road plots compared to control and walkway plots. At the location where basal shear stress reaches a critical threshold, or rainsplash is unable to obliterate incipient channels (usually 20 to 40 meters from the road berm), channel initiation occurs and channel heads are abundant.

Rock alignments act as barricades to flow. Rock alignments, which outline walkways, are usually orientated 20° from the steepest average gradient of the Iron Mountain piedmont. When small flows encounter the large rock clasts (or when channels form inside walkway boundaries), the water is forced along the alignments until the rock alignment ends, the flow acquires enough power to breach the rock alignment, there is a gap in the alignment, or the channel diffuses into the surface. The most common channel orientation in walkway plots is along the rock alignments, and some channels flow inside walkways for the entire length of the plot.

The length of time that the drainage network will continue to be affected by past Army activities is difficult to determine. Webb et al. (1986) suggested that soil densities might take more than a

Figure 9. Photograph of the smooth surface below an intact road berm on map C-4. This area, devoid of channels, is dominated by sheetwash. Bush in center of photograph is ~2 m high.

Figure 10. Photograph of a wide, braided channel down gradient of a breached berm in R-1. Bush in front left is ~80 cm high.

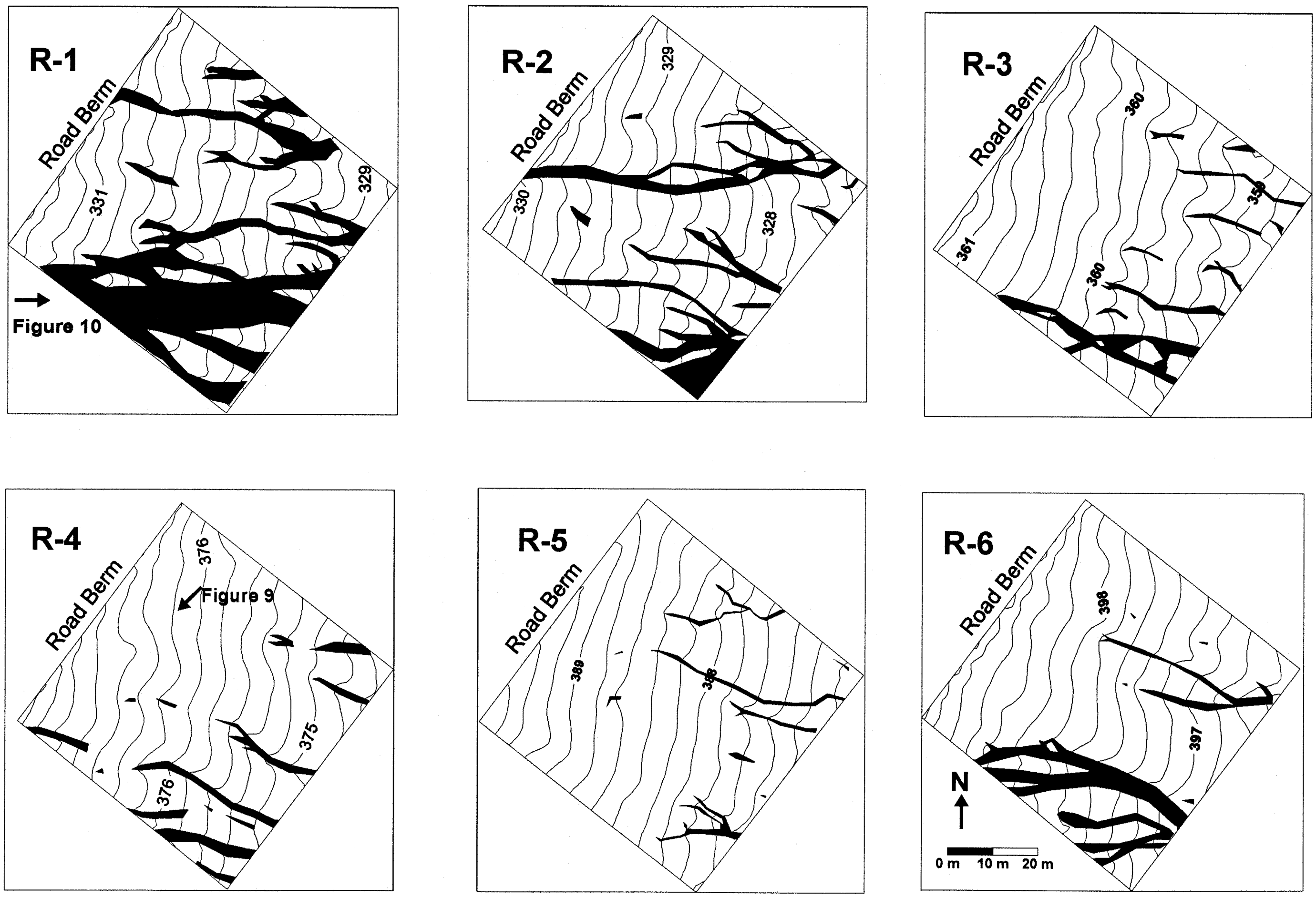


Figure 11. Maps of all road plots. Scale bar and direction are in R-6. Contour interval = 0.2 meters. Road berms form the up-gradient boundary. Area where channel heads are absent is 20 m–40 m wide. Location of Figure 9 photograph is noted in R-4. Location of Figure 10 photograph is noted in R-1. Elevations in maps are precise to ± 1 cm, but real elevations are ± 30 m, due to systematic GPS inaccuracy.

century to recover to natural values after disturbance. Iverson (1980), Iverson et al. (1981), and Prose (1985) conclude that soil lost by erosion in desert environments is probably unrecoverable on human time scales. We observed that more than half of the road berms and rock alignments are still intact more than 50 years after camp abandonment. Since soil compaction is probably only halfway to recovery and rock alignments and road berms will be present for the next 50 years, drainage networks should be affected for at least that long and possibly longer.

Persisting army effects might have been significantly reduced by simple remediation at the time of camp abandonment. Because the topography was smooth within camp boundaries and the roads were already compacted (Prose, 1985), grading the road berms at abandonment would have eliminated local drainage divides without further disturbing the surface. Also, removal of the rock alignments would have eliminated the stone-walled flow boundaries. Neither of these techniques, however, addresses compaction or smoothing of roughness elements, which are more difficult to remediate. Nevertheless, the removal of road berms and rock alignments in 1944 would have greatly reduced many of the lingering hydraulic differences demonstrated by our data.

CONCLUSIONS

Camp Iron Mountain is located on a uniform, low gradient, piedmont surface where sediment is transported primarily in shallow, discontinuous, ephemeral streams. After two intense years of military activity and 54 subsequent years of recovery, channels in affected areas still have not returned to natural geometries due to: (1) the persisting network of road berms and rock alignments, and (2) soil compaction and smoothing. Road berms concentrate runoff and cause zones where channels are absent below intact road berms. Where berms are breached, wide, braided channels dominate. Discontinuous rock alignments disperse flow and inhibit channel formation. Continuous rock alignments influence the orientation and increase the frequency of small channels, but not large channels. Compacted and smoothed walkway surfaces change channel morphologies. Destroying road berms and rock

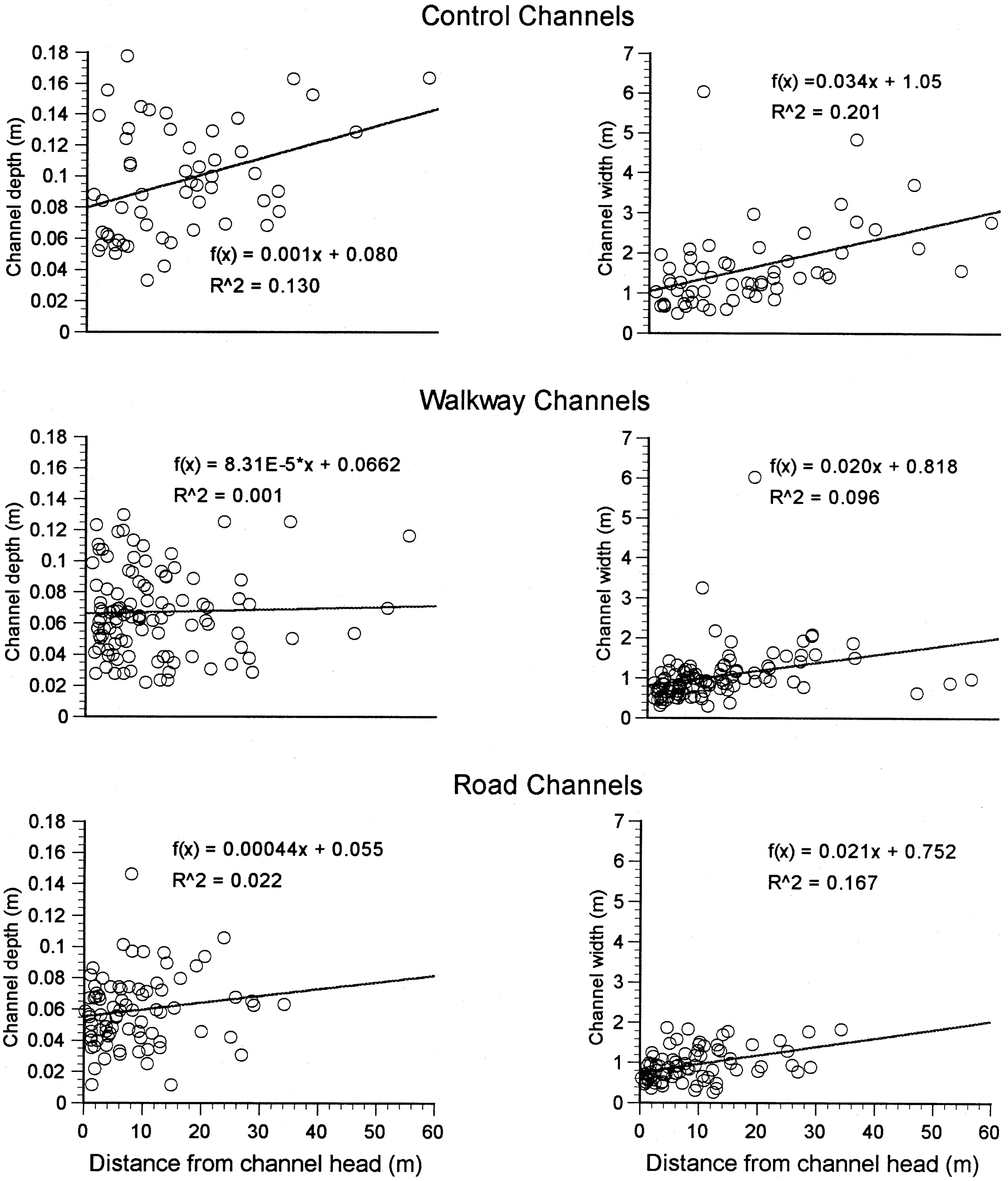


Figure 12. Channel widths and depths as a function of distance from channel head. Low slopes of linear models and poor correlation imply that channels widen slightly but do not appear to deepen significantly down piedmont

alignments when temporary camps are abandoned will likely minimize the long-term impact of army maneuvers.

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