Landform Analysis, Vol. 2: 5–18 (1999)

Cinder movement experiments on scoria cones slopes: Rates and direction of transport

Donald M. Hooper

Department of Geology,
State University of New York at Buffalo,
Buffalo, N.Y. 14260-3050 U.S.A.

Landform Analysis
1999

Abstract: As part of a field experiment to examine slope processes, four experimental grids with painted and numbered cinders were placed on the outer crater rims of two scoria cones in the San Francisco volcanic field, Arizona. Each grid contained 50 cinders placed in five rows of ten each. Rows were placed parallel to local slope contours. The mean diameter for each cinder was 1.7±0.2 cm (n = 200) and the average grid slope was 20.2°. Grids were set in July 1992. They were revisited one month later in August 1992 and again two years later in August 1994. Although several cinders failed to show any movement in the August 1992 survey, the average length of movement was 11.2 cm (n = 118). If the total movement is averaged over the 197 cinders that were relocated, the average length of movement then becomes 6.7 cm (n = 197). All cinders showed movement in the August 1994 survey and the average distance of movement was 32.8 cm (n = 141 with 59 missing cinders). The mean annual rate of movement after 25 months was 15.8 cm/yr (n = 141).

Using the convention that the 180° azimuth direction is downslope and perpendicular to local slope contours, the direction of cinder movement more closely approaches 180° with an increase in time. The azimuth directions calculated after just one month of emplacement display greater scatter and variability than the more correlated results measured after 25 months. The mean azimuth value after the 1992 survey was 163.6±54.2° (n = 118), while the mean azimuth after the 1994 survey was 177.9±20.7° (n = 141). Several painted cinders displayed upslope movement when the grids were first visited after one month. However, after two years the cumulative movement for every cinder was downslope from its original position. Non-channel overland flow is interpreted to be the primary erosional agent responsible for moving the cinders in the downhill direction. Rainsplash is interpreted to be responsible for moving the cinders in the upslope direction and is believed to be the major contributor to the variability in the azimuth measurements.

Key words: erosion rates, San Francisco volcanic field, downslope transport, cinder cone, scoria cone, surficial processes, rainsplash, slope wash, overland flow, hillslope processes

Introduction

Most scoria cones (also known as "cinder" cones) are conical structures of ballistically ejected fragments topped by a bowl-shaped crater. These small volcanoes are usually similar in structure and composition and may cluster by the dozens or even hundreds in volcanic fields or on the flanks of larger volcanoes. Youthful cones have a loose and permeable mantle of pyroclastic material, while older cones are characterized by a degraded coneform and an extensive debris apron around the base of the cone. Often the slopes of an older cone will display signs of hydraulic action or overland flow, such as rills or even a more extensive gully network.

A variety of processes can be responsible for eroding a hillslope, including rainsplash, soil creep, freeze-thaw movements, numerous types of mass movements, and running water (slope wash or sheet wash, rilling, and gullying). Scoria cone degradation has been attributed to small debris flows and rilling processes (Dohrenwend *et al.*, 1986; Renault, 1989). Segerstrom (1950, 1960) studied the erosion of the historically active (1943 to 1952) Parícutin scoria cone in Mexico. He noted that rill erosion had not started on the sides of the cone and that the tephra was still too coarse and permeable to permit surface flow of rainwater. He further observed that the ash mantle covering both the cone and surrounding terrain is gradually being removed by raindrop splash, sheet wash, landsliding, channel erosion, and deflation by wind. Wood (1980) cited the importance of weathering on scoria cone slopes and used simple models to quantify cone degradiation. By incorporating a diffusion-equation method to model surficial processes, Hooper (1995) and Hooper & Sheridan (1998) applied this computer-simulation approach to measure cone degradation in several volcanic fields.

There is a considerable number of publications concentrating on the absolute rates of operation of geomorphological processes on slopes. Excellent summaries can be found in Young (1972), Saunders & Young (1983), and Bryan (1991). However, the number of studies specifically focussing on the slope processes occurring on volcanic landforms is limited. The purpose of this study is to provide more information on the degradation of scoria cone slopes in the semi-arid climate of the San Francisco volcanic field and to identify and measure the erosional effectiveness of the various hillslope processes. This study is unique in that the particles are pyroclastic fragments (cinders) and that the movement of each individual stone or cinder is measured in detail.

Setting

The San Francisco volcanic field of north-central Arizona (U.S.A.) consists of late Miocene to Holocene volcanic rocks (Fig. 1). Previous researchers (e.g., Moore *et al.*, 1974; 1976; Tanaka *et al.*, 1986; 1990) have identified more than 600 volcanoes with their associated lava or pyroclastic flows. Although volcanic landforms with a basaltic composition are dominant, several intermediate to silicic volcanic centers have been recognized. San Francisco Mountain, the remnants of a large stratovolcano with an elevation of 3850 m a.s.l. (above sea level), is the dominant physiographic and volcanic feature in this field.

The San Francisco volcanic field has an average elevation of approximately 2100 m and is situated upon the southern margin of the Colorado Plateau. The climate over most of the field is semi-arid. Mean annual precipitation, which increases with elevation, is 503 mm in Flagstaff (elevation of 2135 m) (Sellers & Hill, 1974). From early July until early September, afternoon thunderstorms develop almost daily over the higher terrains. These convective storms are usually short-lived and are triggered by moist, tropical air flowing into Arizona from the Gulf of Mexico (Sellers & Hill, 1974). Additional precipitation is provided by winter frontal storms that enter the state from the west after picking up moisture from the Pacific Ocean.

The experimental grids were set in July 1992. They were revisited a month later (roughly 30 days later) in August 1992 and again two years later in August 1994.

The grids were placed on two scoria cones, Black Bottom Crater in the eastern portion of the San Francisco volcanic field and an unnamed cone in the central portion of the field containing Walker Lake (Fig. 1).

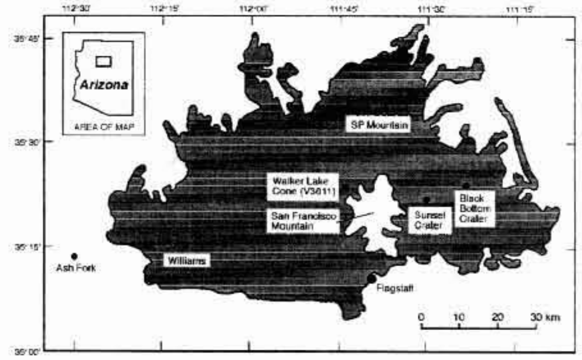

Fig. 1. San Francisco volcanic field, Arizona, showing the locations of the study sites at Black Bottom Crater and the Walker Lake cone. Gray pattern represents Pliocene and Pleistocene volcanic rocks (boundaries from Tanaka *et al.*, 1986). A few other significant volcanic edifices are also labeled. Flagstaff is the most populous city in the region.

Geologic mapping by Moore & Wolfe (1987) assigned a middle Pleistocene age to Black Bottom Crater. They also employed a four-digit numbering scheme to identify the volcanic vents in this field and this scoria cone was designated V3901. Black Bottom Crater is located in the Strawberry Crater quadrangle of the 1:24,000-scale series of topographic maps (Department of the Interior, U.S. Geological Survey). The cone has a slightly NE-SW elongation and the maximum crater rim elevation is 6332 ft (1930 m). Cone height, defined as the difference between average basal elevation and maximum crater rim elevation, was calculated to be 162 m. Crater depth, defined as the difference between maximum crater rim elevation and crater bottom elevation, was calculated to be 80 m. Reaching a maximum width of 5 m and a maximum depth of nearly 3 m, there are several gullies at the base of the north-facing slope of Black Bottom Crater. Some smaller rills are also present.

The second cone, designated V3611 by Wolfe *et al.* (1987), lies in the central region of the volcanic field. It is located in the White Horse Hills quadrangle of the 1:24,000-scale series of topographic maps (Department of the Interior, U.S. Geological Survey). This cone has a maximum crater rim elevation of 8511 ft (2594 m), a cone height of 156 m, and a crater depth of 98 m. It has a shallow body of water within the crater named Walker Lake. Some large gullies can be found on the east and west cone flanks. A K-Ar age from this cone yielded a late Pliocene date of 2.01±0.22 Ma (Wolfe *et al.*, 1987; Tanaka *et al.*, 1990). Additionally, this cone has recently been studied by Blauvelt (1998).

Experimental grids and procedures

A total of four experimental grids were placed on both the north and south crater rims of Black Bottom Crater (V3901) and the Walker Lake cone (V3611). The grids were emplaced on the north and south rims of each crater to test for microclimate effects. More specifically, they were placed on the outer cone slopes rather than on the inner slopes of the crater. For example, a grid on the north crater rim has a northern exposure while a grid on the south crater rim has a southern exposure. Each grid contained 50 painted lapilli-size stones (or "cinders") placed in five rows of ten each with each stone being placed 10 cm from its neighbor. Each row was placed parallel to the local slope contours, and the position of the cinders was established with reference to wooden stakes at the grid corners. Each stake was approximately 30 cm in length. The long and short axis of each cinder, usually between 1 and 2 cm, was measured to determine the average diameter. The mean diameter for all 200 cinders was 1.7±0.2 cm.

Each experimental cinder was spray-painted white and received an identifying numeral painted in black. The numbering and coordinate systems for each grid were arranged so that the first row of cinders is numbered 1–10 and is upslope from the last row (cinders #41–50). Stake #1 is near cinder #1 and is located at position (0, 0). Stake #2 is near cinder #10 at position (110, 0), while stake #3 is at (0, 60) near cinder #41 and stake #4 is at (110, 60) near cinder #50 (see Figs. 2 and 3). Downslope has been defined as the positive y-axis direction.

In order to record the natural movement of these pyroclastic fragments on the hillslope, the objective was to choose a site that required little modification or landscaping. Relatively unvegetated sites with bare soil and cinders were selected. Very little vegetation was removed and smoothing or grading of the site was also kept to a minimum. The slope of each grid was measured in three locations with a clipboard and clinometer (pocket transit). Each grid had roughly a 20° average slope. As the cinders were transported downslope beyond the control area of the grid, the slope angle may become more variable; thus creating a potential source of inaccuracy or error.

Grid 1 was placed at an elevation of 6250 ft (1911 m) on the north crater rim (facing north) of Black Bottom Crater. Elevation measurements were made with a hand-held electronic altimeter and checked against the 7.5 minute topographic maps. The surface of the grid has an average slope of 20° dipping to the north (north is the downhill direction at this grid).

The second grid was placed at an elevation of 6240 ft (1902 m) on the south rim (facing south) of Black Bottom Crater and slopes 23° to the south (south is the downhill direction at this grid).

Grid 3 was emplaced on the north crater rim (facing north) of the Walker Lake cone at an elevation of 8480 ft (2585 m). The surface of the grid has an average slope of 19° to the north. This cone is heavily forested, but the grid is located in a clearing from a brush fire (charred logs are common on the cone slopes around this site).

The fourth grid was emplaced at an elevation of 8300 ft (2530 m) on the Walker Lake cone. Because of the difficulty in finding a clearing in the extensive tree growth and the proximity of a dirt trail, this grid was put on the south-southwest slope and therefore faces south-southwest. The average slope for this grid is 19°.

Results from summer 1992

The experimental grids were set in July 1992 and revisited roughly 30 days later in August 1992. Although seasonal thunderstorms are often scattered and isolated, at least one thundershower was witnessed at each of the study sites. On-line precipitation records from several local stations also verify July and August rainfall (National Climatic Data Center; see Table 1). Upon revisiting the scoria cones, cinder movement was recorded by tape measure with reference to the corner stakes or pegs. Several cinders showed no movement (no detachment from soil or cinder mantle). A few cinders moved a distance of over 40 cm from their original positions, but the average length of movement was 11.2 cm (n = 118). If the total movement is averaged over all 197 cinders that were relocated, the average length of movement then becomes 6.7 cm (n = 197). The direction of movement was calculated afterwards by using the convention that the 0° azimuth direction is upslope and the 180° azimuth direction is downslope. Upslope and downslope are defined as being perpendicular to the local slope contours or perpendicular

Table 1. Monthly precipitation data (mm) for Flagstaff, Arizona (Pulliam Airport, Station 023010)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1992	51.6	93.7	111.8	19.8	105.2	8.1	67.8	147.3	0.0	92.4	11.7	172.2	881.6
1993	242.6	255.3	39.1	6.6	11.2	14.0	0.0	106.4	49.5	83.6	76.7	19.3	904.3
1994	9.6	62.7	77.0	63.0	25.6	-[1]	43.2	91.7	69.8	28.4	48.5	36.3	555.8[2]

Source: World Monthly Surface Station Climatology Data, National Climatic Data Center, Asheville, North Carolina (U.S.A.), NCDC On-line data access (http://www.ncdc.noaa.gov).

[1] incomplete or missing data.

[2] represents a minimum value. All precipitation amounts are in mm.

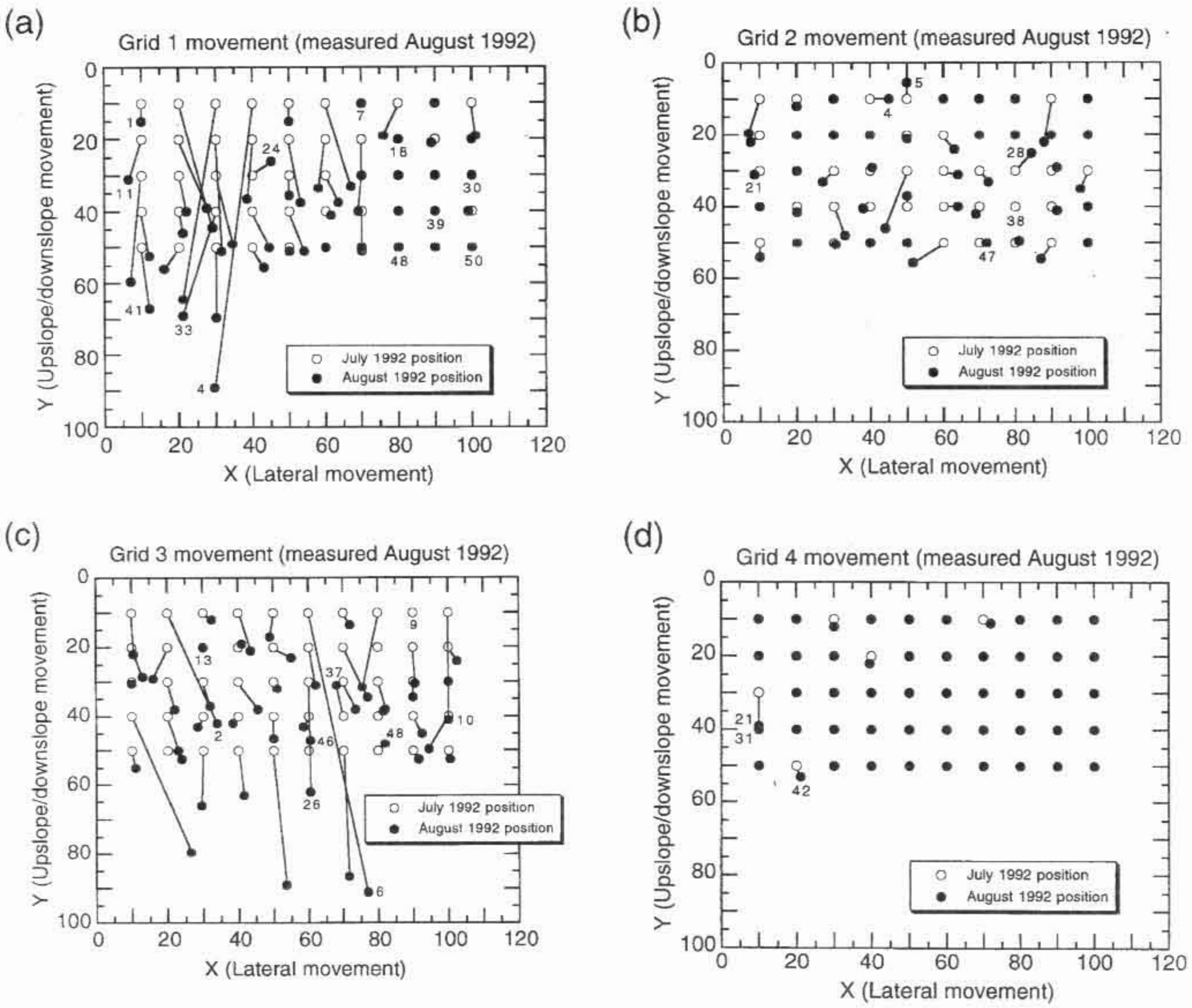

Fig. 3. Plots depicting the movement of individual cinders as measured in August 1992 (solid circles). Open circles are the original July 1992 positions. For reference, stake #1 is at position (0, 0), stake #2 at (110, 0), stake #3 at (0, 60), and stake #4 at (110, 60). (a) Grid 1. Some cinders show no movement (e.g., #7, 39, 50), while cinder #24 displays upslope movement. (b) Grid 2. Cinder #38 was missing. (c) Grid 3. (d) Grid 4. This site recorded very little cinder movement.

to the rows of cinders. Table 2 summarizes the important statistical information regarding the changes in each grid, while the Appendix lists the position, amount of movement, and direction of movement for each cinder after both field surveys.

After one month, 37 cinders moved from their original positions in grid 1. The remaining experimental stones showed no movement. Although the predominant direction of movement was downhill towards the 180° azimuth, two cinders showed uphill movement. One cinder traveled nearly 80 cm downhill, but the average distance each cinder moved was 15.4 cm (n = 37). Two shallow depressions mark one corner of the grid (Fig. 2a). These depressions were probably created by an animal, but the pattern of displacement was not judged disruptive enough to prevent the use of the recorded measurements (Fig. 3a). It appears that some cinders moved into and along the depressions rather than having been buried or pushed aside. Based upon

Table 2. Descriptive statistics for changes in the experimental grids

Grid	Mean distance moved (cm)	Mean direction moved with 1σ	n
Measured August 1992			
Grid	Mean distance moved (cm)	Mean direction moved with 1σ	n[1]
1	15.4	176.2 ± 31.7°	37
2	4.5	152.0 ± 76.8°	30
3	12.8	160.7 ± 52.2°	46
4	3.7	166.2 ± 30.8°	5
1–4	11.2	163.6 ± 54.2°	118
Measured August 1994			
Grid	Mean distance moved (cm)	Mean direction moved with 1σ	n[2]
1	26.5	187.5 ± 16.7°	41
2	24.6	176.0 ± 23.4°	42
3	113.8	179.0 ± 14.8°	17
4	14.0	169.7 ± 20.0°	41
1–4	32.8	177.9 ± 20.7°	141

[1] n is the number of relocated cinders that showed movement from their original July 1992 positions and σ is the standard deviation.
[2] n is the number of relocated cinders after 25 months and σ is the standard deviation.

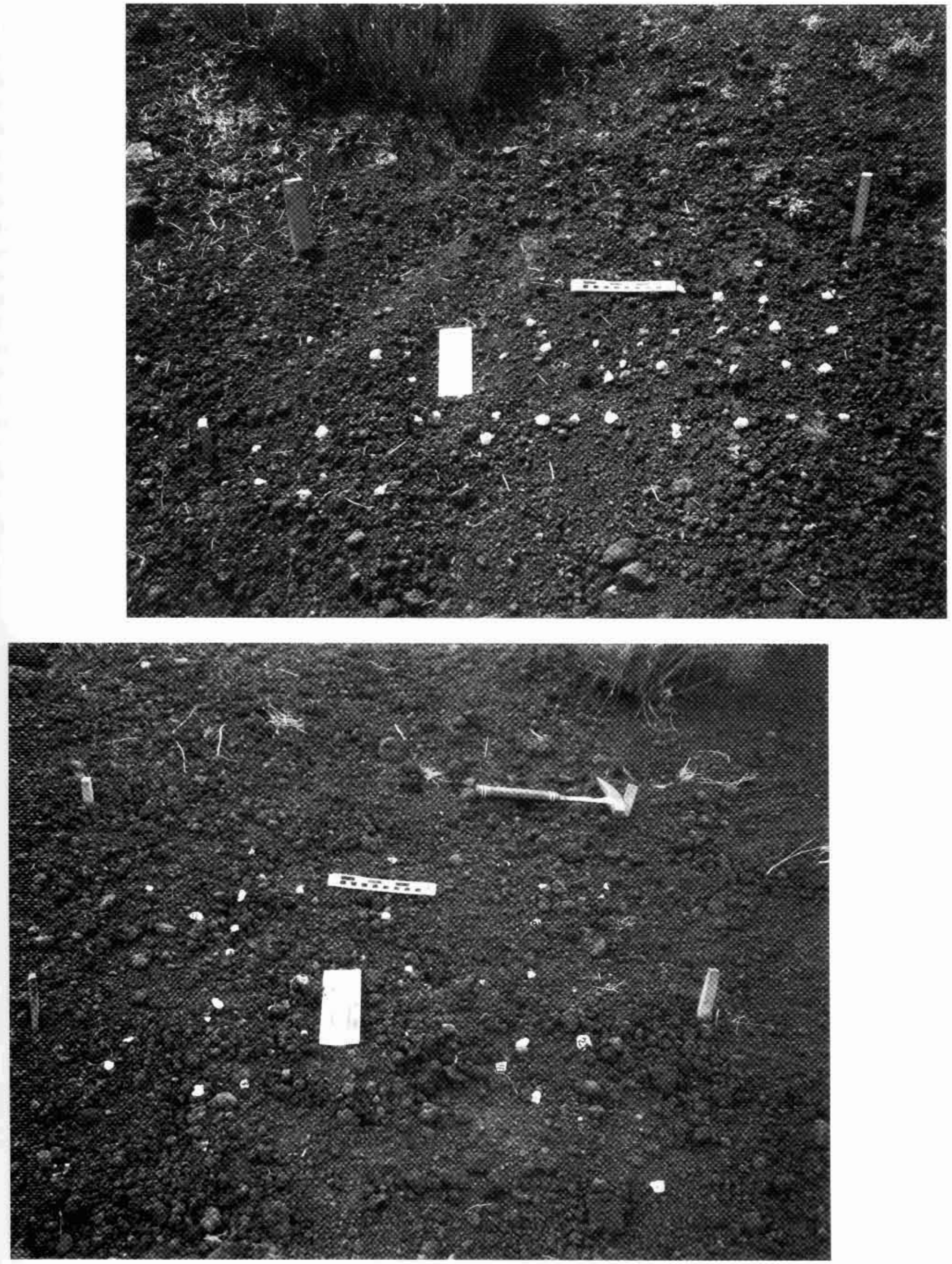

Fig. 2. Selected photographs of the experimental grids. Each cinder was originally placed 10 cm from its neighbor (field rulers and rock hammer for scale).
(a) Grid 1 on August 4, 1992, showing movement of white-painted cinders and two grooved disturbances across one corner of the grid. Uphill is to the top of the photograph. (b) Grid 2 on August 16, 1994, showing 25 months of particle movement. Uphill is to the top of the photograph. (c) Grid 3 on August 17, 1994, showing several considerable changes. Downhill is to the top of the photo-

graph. Two corner stakes are lying on the ground near their original positions, another is hidden from view against the handle of the rock hammer, and the fourth is missing. Note the small log or branch washed into the confines of the grid and the large log 1.5–2 m downhill from the bottom of the grid. The smaller log obscures an animal burrow located near it. Sediment has accumulated beside the larger log. (d) Grid 4 on August 17, 1992, showing a minimal amount of movement after one month. Note the tree shadow and the coarse grain size of the surrounding cinders. Uphill is to the top of the photograph.

field observations of the local area, these grooved disturbances are probably not rills created by hydraulic action.

Thirty cinders had a measurable change in position for the second experimental grid atop Black Bottom Crater. One cinder (#38) could not be found, but it can easily be deduced that the cinder was buried because it was found two years later during the 1994 survey. The average distance of movement was 4.5 cm (n = 30). Six cinders showed uphill movement, while three others had movement parallel to the local slope contours (either an azimuth direction of 90° or 270°). No other grid recorded this much movement in an upslope direction (Fig. 4). This movement in an upslope direction is interpreted to be a manifestation of rainsplash, and will be discussed and analyzed in a later section.

For grid 3, on the northern crater rim of the Walker Lake cone, 46 cinders recorded a change in position after one month. Two cinders showed no movement, while the other two could not be found and presumably were buried, moved an exceptionally large distance downslope, or were removed by an animal. Six cinders, including one that moved in a 90° direction, had an uphill direction of movement. One experimental stone traveled 82.8 cm downslope, the most recorded in this first survey. The average distance of movement was 12.8 cm (n = 46).

Only five cinders moved in grid 4. The average distance of movement was only 3.7 cm (n = 5), the lowest for any grid. No upslope movement was recorded. Since this region of the crater rim is forested, the lack of movement can be attributed to a nearby tree, a Ponderosa Pine (*Pinus ponderosa*). Located to the northeast of the grid, the trunk of the tree measured 11 ft (3.4 m) from the nearest corner stake of the grid. Although not directly overhead, the branches undoubtedly played a role in sheltering the grid from rain. Some pine needles

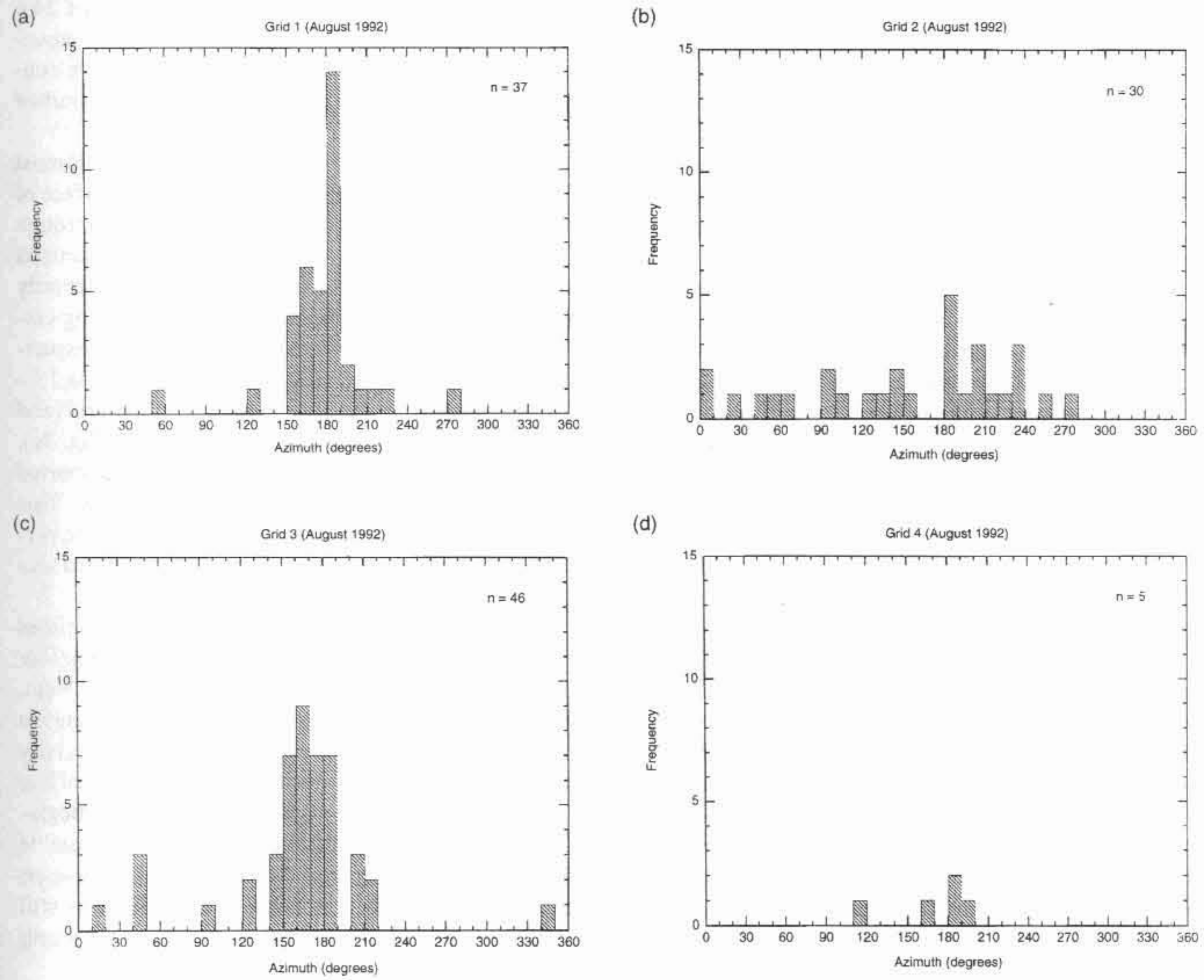

Fig. 4 (a, b, c, d). Histograms for each grid displaying directional data for cinder movement as measured in August 1992 (one month after emplacement). Azimuth represents the direction of movement with the 180° azimuth direction being downslope and perpendicular to the local slope contours (or perpendicular to the rows of cinders). Data are plotted in 10° class intervals (bins) and n is number of observations (in this case cinders with measurable movement).

(and an occasional pine cone) are also interspersed amongst the cinder, probably further inhibiting the movements of the marked stones. Additionally, compared to the other grids, this site was emplaced in the coarsest-grained material. Several fragments within and around the grid measured over 3 cm in diameter (Fig. 2d). While the lack of movement within this grid may initially be disappointing, it does indicate that certain factors may inhibit downslope movement of lapilli-size fragments.

Results from summer 1994

The field sites were again visited in August 1994, two years after they were last visited or 25 months since the grids were initially emplaced. All painted cinders now had measurable movement, but over 50 of the original 200 stones could not be found (Fig. 5). In addition to the possibility of being buried, washed downslope beyond the search area, or removed by animals, some experimental cinders may have become unrecognizable due to chipping and removal of the identifying paint. As anticipated, there is now an even more pronounced downslope trend towards the 180° azimuth as the pyroclastic material continues the long-term process of being transported towards the debris aprons around the base of the cone (compare Figs. 4 and 6). The minimum recorded movement was approximately 4 cm by two different cinders, while the maximum recorded movement was 183.0 cm. As presented in Table 2, the average distance of movement was 32.8 cm (n = 141).

A few cinders have come to rest against larger pyroclastic fragments or against vegetation. These particles have reached a semi-stable juxtaposition and have at least temporarily halted their downslope movement. Several cinders were found partially buried and a few were found completely buried.

Forty-one cinders were relocated around grid 1 on Black Bottom Crater. As observed at each grid, every cinder now showed movement from its original position. One other cinder (#24) was relocated but discarded from the survey because it was found nestled amongst some rocks (volcanic blocks) and branches over 250 cm and at an azimuth of 233° from its original position. Its ensconced positioning indicates that it was most likely transported or disturbed by an animal. The remaining experimental stones could not be relocated. The average distance each cinder moved from its original position was 26.5 cm (n = 41), an increase from 15.4 cm (n = 37) for those cinders in this grid that had a measurable displacement after the first survey in 1992. Several azimuth measurements greater than 180° in grid 1 suggest the possibility of a slight local tilt in the grid surface towards an angle greater than the 180° azimuth direction (Table 2 and see Figs. 5 and 6). However, this should be viewed in its proper context as each grid has minor surface undulations and other imperfections.

A comparison of Fig. 3a, Fig. 5a, and data provided in the Appendix indicates that while cinder #11 exhibited movement towards the side margin of grid 1, it also displayed an uphill displacement from its position recorded during the August 1992 survey (but it still maintained an overall downslope displacement from its original July 1992 position). This is the only cinder in the August 1994 survey that demonstrated an upslope movement during the two years since the 1992 measurements.

A total of 42 cinders were relocated at grid 2, the second site atop Black Bottom Crater. They had an average displacement or movement distance of 24.6 cm (n = 42). Cinder #37, with its direction of movement being 242°, appears slightly anomalous in context with the rest of the grid and was perhaps disturbed by an animal (Fig. 5b).

Grid 3 experienced significant modifications most likely related to overland flow. The ground surface of the grid itself appears to have been lowered through the loss of material, as suggested by exposed portions of root systems in the surrounding vegetation (mostly grasses). Material washed downslope, including cinders and soil removed from the confines of the experimental grid, has collected against a long log lying 1.5–2 m downhill from the bottom margin of the grid (and slightly diagonal to the margin of the grid) (Fig. 2c). More material has been dislodged and transported downslope at this grid than at any of the others. This area has certainly been subjected to overland flow, perhaps even minor channelized flow in unvegetated sections, and could be the site of an incipient gully.

No painted cinders remained within the confines of grid 3 and only 17 could be found downslope (Fig. 5c). These had an average displacement of 113.8 cm, by far the most for any grid (Table 2). An extensive search was made for the remaining cinders, especially amongst the sediment deposited against the charred log, but few could be located. Some cinders were beginning to lose their identifying paint and it is possible that the paint chipped and flaked off during transport or weathering. Only one corner stake (#1) was still emplaced; two were lying on the ground and the fourth

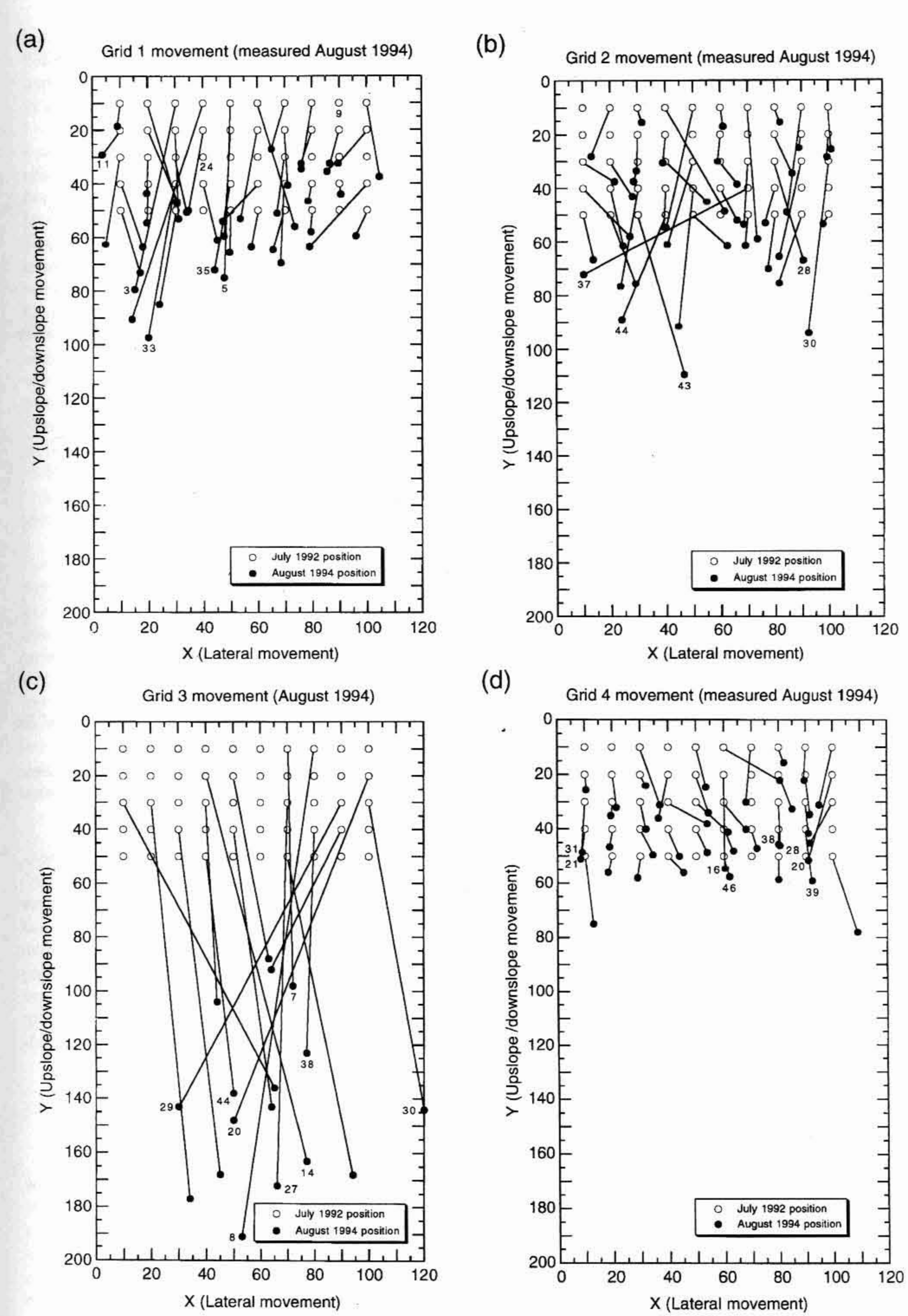

Fig. 5 (a, b, c, d). Plots for each grid illustrating the movement of individual cinders as measured in August 1994 (solid circles). Open circles are the original July 1992 positions. All cinders now show movement after 25 months of emplacement, but many marked cinders could not be located (shown as open circles in their original positions).

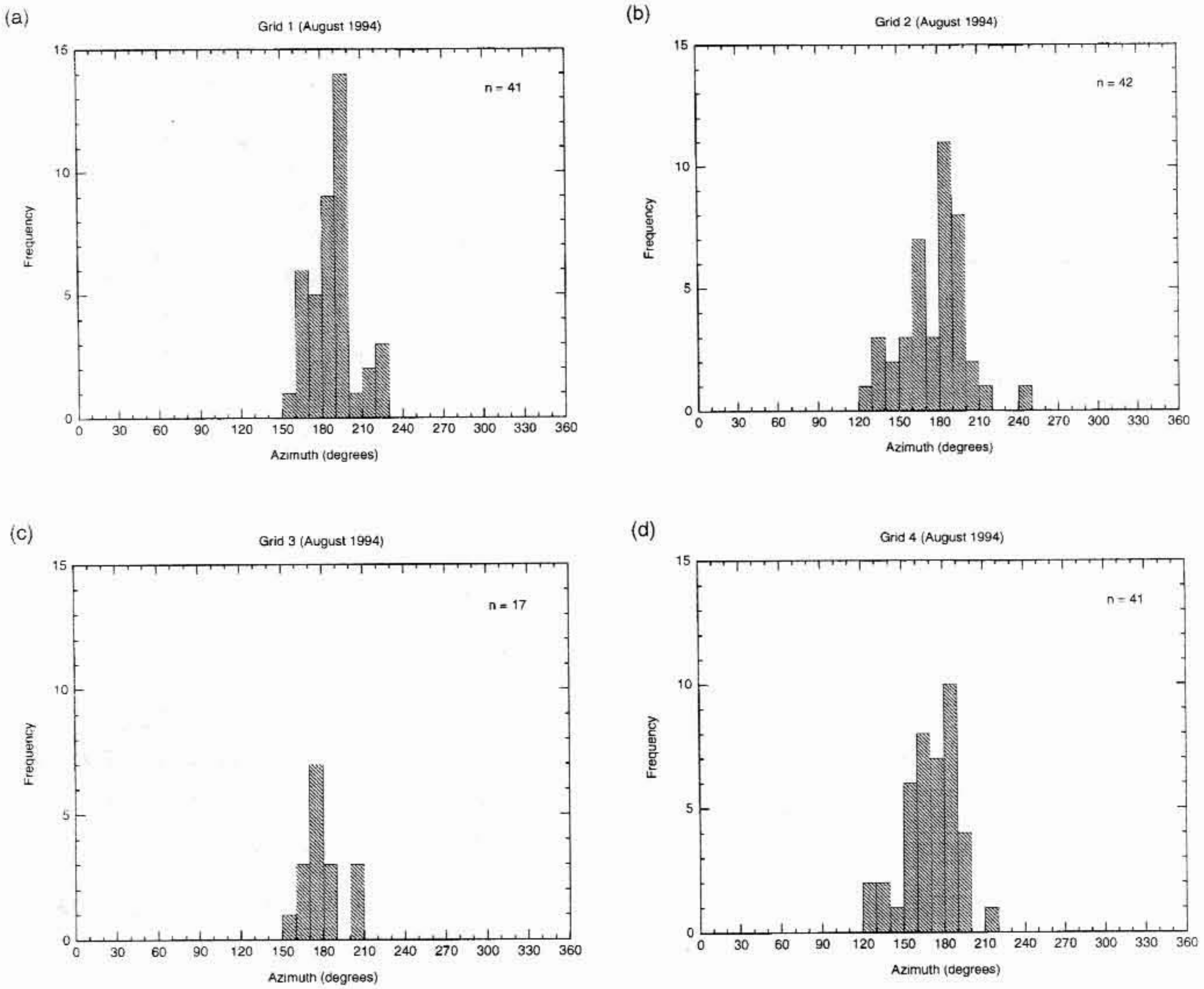

Fig. 6 (a, b, c, d). Histograms for each grid displaying azimuth measurements as recorded in August 1994 (25 months after emplacement). The 180° azimuth direction is defined as downslope and perpendicular to the local slope contours. Data are plotted in 10° bins and n is number of observations (all relocated cinders had measurable movement).

could not be found. Natural processes most likely played a part in dislodging the stakes, although human interference cannot be entirely eliminated because two soda cans and a spent rifle shell were found in the vicinity. These were perhaps left by a hunter in pursuit of the deer attracted to the waters of the crater lake.

Grid 3 also had an approximately 20 cm-long charred segment of a tree branch resting within it (Fig. 2c). This branch can be seen lying upslope from the grid in 1992 photographs. A final disturbance to the grid consisted of an animal burrow with a diameter of about 8 cm located just above the first row and roughly between the original sites of cinders #5 and #6. The cinder displacement patterns and other observations recorded at this site suggest that overland flow is more responsible for cinder movement than rainsplash.

A total of 41 cinders were relocated at grid 4, the second site atop the Walker Lake cone. They had an average movement of 14.0 cm (n = 41), again the lowest value for any of the grids.

The grid sites were again visited in September 1996, but on 21 June 1996 a wildfire (named the "Hochderffer fire", U.S. Forest Service) swept over the Walker Lake cone, burning the remaining wooden stakes and rendering the painted cinders unrecognizable. Upon returning to Black Bottom Crater, the stakes marking grid 2 could not be relocated. Their exact fate remains undetermined. Although measurements were made for grid 1, the field experiment at this point was considered to be concluded.

Analysis and discussion

Precipitation data recorded during the course of the field experiment are summarized in Table 1. This meteorological station at the Flagstaff airport is one of the closest to both scoria cones and represents the station with the most complete record of precipitation data recorded in 1992–1994, although it had one month with

missing or incomplete data. A summary of the data in Table 1 reveals that precipitation amounts in 1992 through 1994 were above the 503 mm mean recorded in 1950 through 1970 by Sellers & Hill (1974).

When the grids were first visited after one month, a small percentage of the painted cinders displayed upslope movement from their original July 1992 positions. However, after two years the cumulative movement for every cinder was downslope (Figs. 5 and 6). Overland flow is interpreted to be the primary erosional agent responsible for moving the cinders in the downhill direction perpendicular to the local slope contours (or the rows of cinders). The presence of gullies and rills on the slopes of both selected cones indicates that channelized flow and rilling does occur, but it is less common at the grid sites near the crater rims. The pattern and extensive amount of cinder movement at grid 3 suggests that some channelized overland flow may have developed, but non-channel overland flow appears to be more common. Rainsplash is interpreted to be responsible for moving the cinders in potentially all directions, including upslope.

There are many studies in the literature regarding the various aspects of rainsplash, but two studies will serve to illustrate this process and how it can be identified on scoria cone slopes. Early experiments by Ellison (1944) showed that considerably more soil is splashed downslope than is splashed upslope, producing an asymmetrical pattern of movement. He found that three times as much material was transported downslope than upslope in splashboard experiments on a 6° slope. His experiments also showed that rainsplash transport could cause significant particle movement, including the movement of 0.4 cm stones as far as 20 cm and even smaller particles moving up to 150 cm. Particles moving downslope also traveled greater horizontal distances than those moving upslope.

Another experimental study by Mosley (1974) provided data for the relationship between weight of sand splashed by waterdrop impact, distance from source, and slope angle. He demonstrated that 50% of the total weight of the sand was splashed in what would be the downslope direction when the laboratory apparatus was in a horizontal position, but this figure increases to 95% when the sand surface is inclined at an angle of 25°. Both these studies acknowledge that rainfall at an oblique angle adds a further degree of complexity to the process of rainsplash.

Therefore, we can expect those particles that show upslope movement to have traveled a lesser distance than those that show downslope movement. Although it is difficult at best to separate those cinders that have moved by rainsplash from those that have moved by overland flow, and indeed many have certainly moved by a combination of processes, an examination of the cinder movement data from 1992 does appear similar to the results of Ellison (1944) and Mosley (1974). Of the 118 cinders that demonstrated movement after the first month of emplacement, 17 displayed movement in an upslope direction or in a direction parallel to the slope contours (i.e., 90° or 270°). The average movement for cinders moving downslope was 12.4 cm (n = 101), while those moving upslope moved only an average of 3.4 cm (n = 17). If those particles moving in the 90° and 270° directions are switched to the down-slope category, the results change slightly with the average downslope movement now being 12.0 cm (n = 106) and upslope movement changing to 3.6 cm (n = 12). Therefore, when using the latter set of calculations, roughly 10% (n = 118) of the cinders showing displacement moved in an upslope direction. When the grids were revisited after two years, the cumulative movement for every cinder was downslope. Upslope transport by rainsplash most assuredly is still occurring, but the overall direction of movement has been downslope from the original positions.

The direction of cinder movement more closely approaches 180° with an increase in time (Fig. 7). The

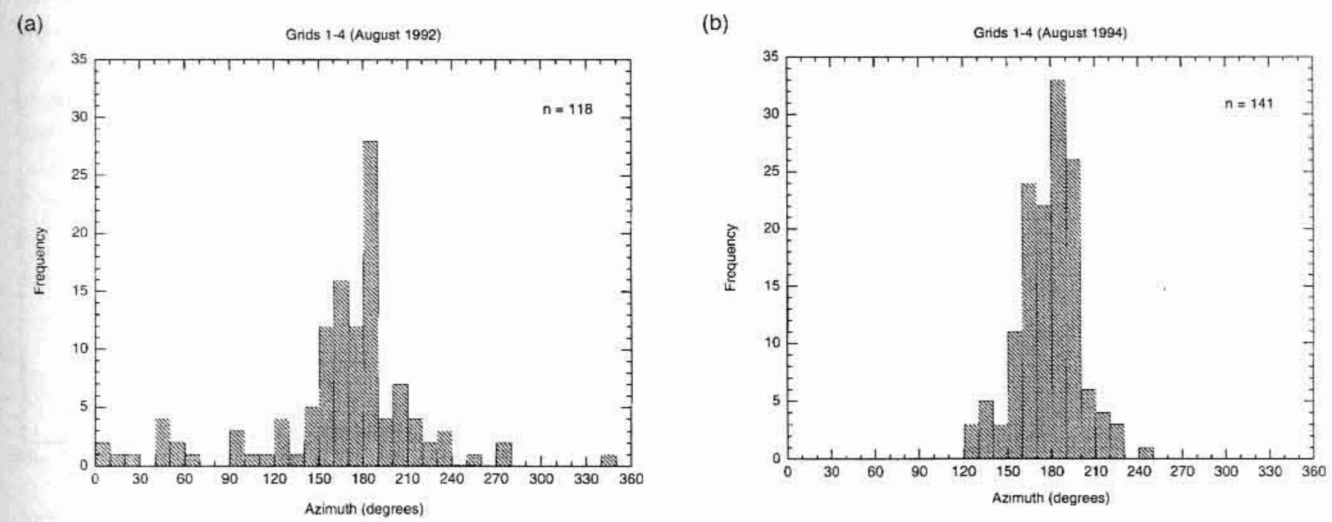

Fig. 7. Frequency distribution of azimuth measurements for all grids as recorded in (a) August 1992 and (b) August 1994.

azimuth measurements calculated after just one month of emplacement display greater scatter and variability than the more correlated results measured after 25 months of emplacement. This is especially evident when comparing the standard deviations (Table 2). Grid 1 is the only grid that has a 1992 mean azimuth value closer to 180° than the 1994 mean azimuth value (this probably reflects a locally tilted grid slope). The mean downslope azimuth value for all cinders after the 1992 survey was 163.6±54.2° (n = 118), while the mean downslope azimuth for all cinders after the 1994 survey was 177.9±20.7° (n = 141). Compared to overland flow processes, rainsplash is believed to be less effective at moving particles directly downslope towards the 180° azimuth. However, it is a greater contributor to the variability of the azimuth measurements.

For calculating the frequency distribution, the histograms reflect a slight bias in recording the movements of the cinders. Surface roughness, non-spherical cinder morphology, and other factors contributed to limiting the accuracy in measuring cinder positions; therefore the measurements were recorded to the nearest half centimeter. Using this approach, cinders that moved directly downslope (i.e., perpendicular to the slope contours) for only a short distance, usually less than 5 cm, were often measured to have a 180° azimuth value. This creates a "clustering" of 180° azimuth measurements. Over a 5 cm distance this causes an uncertainty that approaches 180±6°, the uncertainty increasing with shorter movement distances. Occurring less frequently, there is a similar bias at 0°, 90°, and 270°. Despite this bias, the results from the 1992 azimuth measurements show greater variability than the results from the 1994 measurements. Although the inaccuracy of the measurements still remains, the cinders had moved greater distances after two years and the bias was no longer present in the data from the 1994 survey.

Additionally, the active surface processes of overland flow and rainsplash were also responsible for an increase in the average distance each painted cinder moved with an increase in time (Table 2 and Fig. 8). The rate at which the painted cinders are moving downslope can also be calculated. Using all 141 cinders relocated in the 1994 survey, the mean annual rate of movement after 25 months was 15.8 cm/yr (Table 3).

Table 3. Mean rate of cinder movement measured after 25 months (July 1992–August 1994)

Grid	Rate of movement (cm/yr)	n[1]
1	12.7	41
2	11.8	42
3	54.6	17
4	6.7	41
1–4	15.8	141

[1]n is the number of relocated painted cinders after 25 months.

Comparison with other research

Only a limited number of researchers have employed the technique of painting stones on hillslopes in order to more fully understand the types and rates of erosional processes. Schumm (1967) monitored the movement of thin, platy fragments of sandstone down hillslopes of Mancos shale near Montrose, western Colorado. After a measurement period that spanned seven years, he determined that the rate of movement of the marked stones was directly proportional to the sine of hillslope inclination. The stones in his study ranged in thickness between 3 to 6 mm, and from 25 to 75 mm in maximum dimension. Although the particle size, lithology, climate, and surficial processes are not directly comparable to this study, Schumm (1967) reported rates of movement ranging from a few millimeters per year on a 3° slope to almost 7 cm/yr on a 40° slope. He concluded that creep induced from frost and freeze-thaw activity was the dominant factor causing downslope transport.

Kirkby & Kirkby (1974) painted lines across 12 hillslopes around Tucson in the Sonoran Desert of southern Arizona. Using a two-month (July–August) study period, they recorded after each rainstorm the movement of painted particles with diameters ≥ 1 mm. From their field observations and statistical analyses, they concluded that hydraulic action (non-channel overland flow) and rainsplash were the major processes responsible for moving the painted particles. Their statistical results also suggested that the distance moved was directly related to hillslope gradient, inversely related to particle size, and unrelated to distance from the divide.

More recently, Abrahams *et al.* (1984) analyzed 16 years of painted stone movement on two hillslopes near Barstow in the Mojave Desert, California. They were able to relocate several erosion-monitoring lines established in 1967 by Cooke & Reeves (1972), who only partially completed the interpretation and analysis of this portion of their project. The hillslope profiles examined by Abrahams *et al.* had gradients up to 24°, and they measured stones with a minimum diameter of 8 mm. They concluded that hydraulic action rather than creep is the dominant process on these hillslopes. Furthermore, Abrahams *et al.* noted that the dominance of creep at Schumm's (1967) Montrose, Colorado, field site could be attributed to the higher altitude and more severe winters of that region.

Table 4 compares the present study with data extracted from the studies of Schumm (1967) and Abrahams *et al.* (1984). An attempt was made to use only the data with similar particle size and hillslope angle. The variation in the rates of downslope transport could be attributed to differences in lithology and climate (i.e., surficial processes).

Conclusion

Field observations and statistical analysis identified two major processes responsible for downslope transport of the painted cinders, non-channel overland flow and rainsplash. Channelized flow or rilling may occasionally occur at one of the four experimental grids. Soil creep (and/or solifluction) and frost heave (freeze-thaw movements) could not be identified with certainty, but they may have also contributed to particle movement (although their contribution is considered to be minimal). Non-channel overland flow (and channelized flow when present) is interpreted to be the primary erosional agent responsible for moving the cinders in the downhill direction (180° azimuth). Rainsplash is believed to be a greater contributor to the variability of the azimuth measurements, including the upslope movement of cinders. When the grids were first visited after one month, 12 of the nearly 200 painted cinders displayed upslope movement (5 others moved parallel to the slope contours). However, after two years the cumulative movement for every relocated cinder was downslope from its original position at the beginning of the experiment. Cinders with an upslope azimuth also moved a shorter distance, generally only 25–33% as much as those with downslope movement.

Carson & Kirkby (1972, p. 189) state that "rainsplash can directly move debris of up to at least 1.0 cm diameter and indirectly it can move much larger stones". This study identified rainsplash transport in an upslope direction for cinders with a mean diameter between 1–2 cm. The upslope movement of these pyroclasts was probably facilitated by their vesicular nature and concomitant low specific gravity.

Although the grids were emplaced on both north and south rims of two different scoria cones and each cone had a different crater rim elevation, microclimate effects could not be confidently identified from any of the analyses. A more extensive network of grids and a longer monitoring period may be needed before microclimate effects can be determined.

Although not directly overhead, the branches of a Ponderosa Pine undoubtedly played a role in sheltering one grid from rain and thereby offers at least a par-

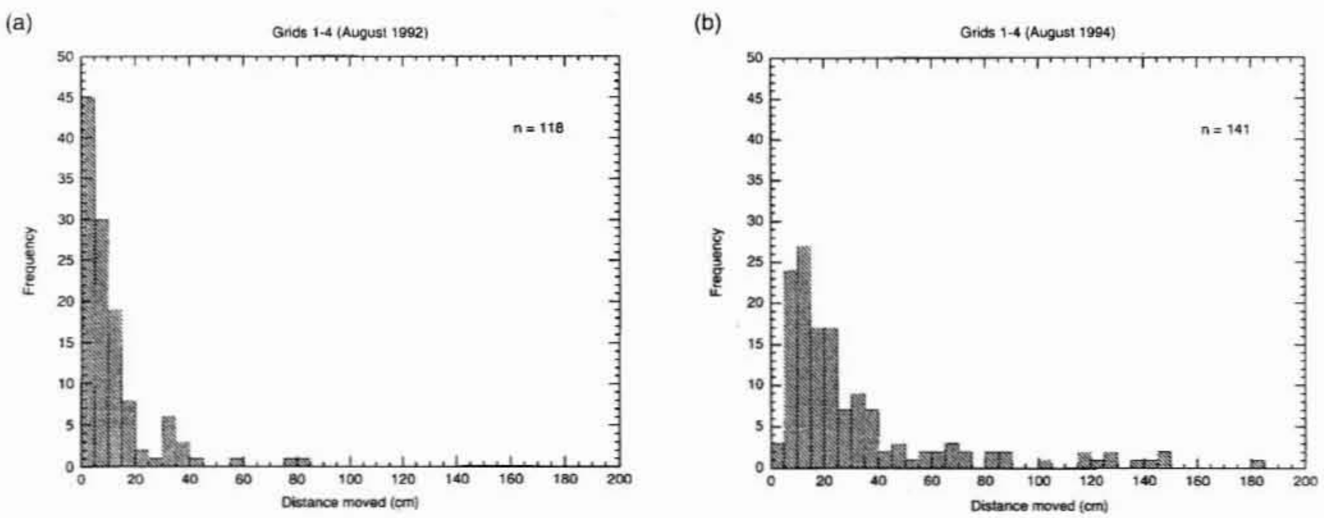

Fig. 8. Histograms illustrating the amount or distance of movement of individual cinders as measured for all grids in (a) August 1992 and (b) August 1994. Data are plotted in 5 cm class intervals (bins) and n is number of observations (cinders with measurable movement).

Table 4. Comparative rates of stone movement

Location and reference	Mean annual precipitation (mm)	Elevation (m)	Slope (degrees)	Stone diameter (cm)	Number of stones	Rate of movement (cm/yr)
Montrose, Colorado (Schumm, 1967)	231	2000	20	0.3–7.5	3	1.9
Barstow, California (Abrahams *et al.*, 1984)	100–200 100–200	730–900 730–900	20 –	– 1–2	4 8	0.094 0.80
Flagstaff, Arizona (This study)	503	2135	20	1–2	141	15.8

tial explanation for the low rate of cinder movement at this site. Animal disturbances also contributed to some cinder movements.

Acknowledgements

The various aspects of the research program to model the degradation of volcanic landforms have been funded by several agencies, including the National Aeronautics and Space Administration (NASA) Graduate Students Researchers Program (NGT-50480/NGT-50691), NASA grant NAGW-2259 (J. King of State University of New York at Buffalo, PI), a Guggenheim Post-doctoral Fellowship (National Air and Space Museum, Smithsonian Institution), and NASA (Mission to Planet Earth) grant NAG-53142 (M. Bursik of State University of New York at Buffalo, PI). The comments, suggestions, and encouragement provided by M. Bursik, P. Calkin, J. King, M. Sheridan, and T. Watters have been greatly appreciated.

References

Abrahams, A.D., Parsons, A.J., Cooke, R.U. & Reeves, R.W., 1984: Stone movement on hillslopes in the Mojave Desert, California: a 16-year record. *Earth Surface Processes and Landforms* 9: 365–370.

Blauvelt, D.J., 1998: *Examples of cinder cone degradation from the San Francisco volcanic field, Arizona.* M.A. thesis, State University of New York at Buffalo, New York (U.S.A.), 120 pp.

Bryan, R.B., 1991: Surface wash. *In:* O. Slaymaker *(Ed.) Field experiments and measurement programs in geomorphology.* A.A. Balkema, Rotterdam: 107–167.

Carson, M.A. & Kirkby, M.J., 1972: *Hillslope Form and Process.* Cambridge University Press, London, 475 pp.

Cooke, R.U. & Reeves, R.W., 1972: Relations between debris size and the slope of mountain fronts and pediments in the Mojave Desert, California. *Zeitschrift für Geomorphologie* 16: 76–82.

Dohrenwend, J.C., Wells, S.G., & Turrin, B.D., 1986: Degradation of Quaternary cinder cones in the Cima volcanic field, Mojave Desert, California. *Geological Society of America Bulletin* 97: 421–427.

Ellison, W.D., 1944: Studies of raindrop erosion. *Agricultural Engineering* 25: 131–136.

Hooper, D.M., 1995: Computer-simulation models of scoria cone degradation in the Colima and Michoacán-Guanajuato volcanic fields, Mexico. *Geofisica Internacional* 34: 321–340.

Hooper, D.M. & Sheridan, M.F., 1998: Computer-simulation models of scoria cone degradation. *Journal of Volcanology and Geothermal Research* 83: 241–267.

Kirkby, A. & Kirkby, M.J., 1974: Surface wash at the semi-arid break in slope. *Zeitschrift für Geomorphologie*, Suppl.-Bd. 21: 151–176.

Moore, R.B. & Wolfe, E.W., 1987: *Geologic map of the east part of the San Francisco volcanic field, north-central Arizona.* U.S. Geological Survey Misc. Field Studies Map MF-1960, scale 1:50,000.

Moore, R.B., Wolfe, E.W. & Ulrich, G.E., 1974: Geology of the eastern and northern parts of the San Francisco volcanic field, Arizona. *In:* T.N.V. Karlstrom, G.A. Swann & R.L. Eastwood *(Eds.) Geology of northern Arizona, with notes on archaeology and paleoclimate; Part 1, Regional studies.* Geological Society of America, Rocky Mtn. Section Meeting, Flagstaff, Arizona, pp. 465–494.

Moore, R.B., Wolfe, E.W. & Ulrich, G.E., 1976: Volcanic rocks of the eastern and northern parts of the San Francisco volcanic field, Arizona. *Journal of Research, U.S. Geological Survey* 4: 549–560.

Mosley, M.P., 1974: Experimental study of rill erosion. *Transactions of the ASAE* 17: 909–913, 916.

Renault, C.E., 1989: *Hillslope processes on late Quaternary cinder cones of the Cima volcanic field, eastern Mojave Desert, California.* M.S. thesis, University of New Mexico, Albuquerque, New Mexico, 121 pp.

Saunders, I. & Young, A., 1983: Rates of surface processes on slopes, slope retreat and denudation. *Earth Surface Processes and Landforms* 8: 473–501.

Schumm, S.A., 1967: Rates of surficial rock creep on hillslopes in western Colorado. *Science* 155: 560–562.

Segerstrom, K., 1950: Erosion studies at Parícutin, State of Michoacán, Mexico. *U.S. Geological Survey Bulletin* 965-A, 164 pp.

Segerstrom, K., 1960: Erosion and related phenomena at Parícutin in 1957. *U.S. Geological Survey Bulletin* 1104-A, pp. 1–18.

Sellers, W.D. & Hill, R.H., 1974: *Arizona Climate.* University of Arizona Press, Tucson, Arizona, 616 pp.

Tanaka, K.L., Onstott, T.C. & Shoemaker, E.M., 1990: Magneto-stratigraphy of the San Francisco volcanic field, Arizona. *U.S. Geological Survey Bulletin* 1929, 35 pp.

Tanaka, K.L., Shoemaker, E.M., Ulrich, G.E. & Wolfe, E.W., 1986: Migration of volcanism in the San Francisco volcanic field, Arizona. *Geological Society of America Bulletin* 97: 129–141.

Wolfe, E.W., Ulrich, G.E., Holm, R.F., Moore, R.B. & Newhall, C.G., 1987: *Geologic map of the central part of the San Francisco volcanic field, north-central Arizona.* U.S. Geological Survey Misc. Field Studies Map MF-1959, scale 1:50,000.

Wood, C.A., 1980: Morphometric analysis of cinder cone degradation. *Journal of Volcanology and Geothermal Research* 8: 137–160.

Young, A., 1972: *Slopes.* Longman, London, 288 pp.

Appendix
Cinder location and movement data for each grid.

Grid 1. Location: north crater rim (facing north) on Black Bottom Crater at an elevation of 1911 m.
Emplaced: July 2, 1992
First field survey: August 4, 1992
Second field survey: August 16, 1994

Cinder	Aug. 1992 position[1]	Distance moved (cm)	Direction moved (deg.)	Aug. 1994 position	Distance moved (cm)	Direction moved (deg.)
1	10, 15	5.0	180	9, 18.5	8.6	187
2	29, 44.5	35.6	165	30.5, 47.5	38.9	164
3	21, 64.5	55.2	189	15, 79.5	71.1	192
4	29.5, 89	79.7	188	14, 90.5	84.6	198
5	50, 15	5.0	180	47.5, 75	65.0	182
6	67, 33	24.0	163	73.5, 56	47.9	163
7	(70, 10)[2]	0	–	65, 27	17.7	196
8	76, 19	9.8	203	76, 34.5	24.8	189
9	(90, 10)	0	–	–[3]	–	–
10	101, 19	9.1	173	104.5, 37.5	28.2	171
11	6.5, 31	11.5	197	3.5, 29	11.1	216
12	27.5, 39	20.4	157	30.5, 46.5	28.5	158
13	31.5, 51	31.0	177	31, 53	33.0	178
14	38.5, 36.5	16.6	185	34.5, 50	30.5	190
15	53, 37.5	17.8	169	47.5, 59.5	39.6	184
16	58, 33.5	13.6	189	53.5, 53	33.6	191
17	70, 30	10.0	180	71, 40.5	20.5	177
18	(80, 20)	0	–	76, 32.5	13.1	198
19	89, 21	1.4	226	86.5, 32.5	13.0	196
20	(100, 20)	0	–	89.5, 32.5	16.3	220
21	7, 59.5	29.6	186	4.5, 62.5	33.0	190
22	22, 40	10.2	169	19.5, 43.5	13.5	178
23	34.5, 49	19.5	167	34, 50.5	20.9	169
24	45, 26	6.4	51	–165, 253[4]	255.6	233
25	50, 35.5	5.5	180	–	–	–
26	63.5, 37.5	8.3	155	–	–	–
27	69, 40	10.0	186	67, 51	21.2	188
28	(80, 30)	0	–	–	–	–
29	(90, 30)	0	–	85.5, 35.5	7.1	219
30	(100, 30)	0	–	–	–	–
31	12, 52.5	12.7	171	18, 63.5	24.8	161
32	21, 46	6.1	170	19.5, 54.5	14.5	182
33	21, 69	30.4	197	20, 97.5	58.4	190
34	44.5, 50	11.0	156	45, 61	21.6	167
35	54, 51	11.7	160	44, 72	32.6	191
36	61.5, 41	1.8	123	47, 54	19.1	223
37	70, 50	10.0	180	68.5, 69.5	29.5	183
38	(80, 40)	0	–	78.5, 46.5	6.7	193
39	(90, 40)	0	–	90.5, 44	4.0	173
40	99, 40	1.0	270	79, 63.5	31.5	222
41	12, 67	17.1	173	17, 73	24.0	163
42	16, 56	6.3	212	–	–	–
43	30, 69.5	19.5	180	24, 85	35.5	190
44	43, 55.5	6.3	152	–	–	–
45	50, 51	1.0	180	49.5, 65.5	15.5	182
46	(60, 50)	0	–	57.5, 63.5	13.7	191
47	70, 51	1.0	180	65.5, 64.5	15.2	197
48	(80, 50)	0	–	79.5, 58	8.0	184
49	(90, 50)	0	–	–	–	–
50	(100, 50)	0	–	96, 59.5	10.3	203

[1] Grid coordinates (x = direction parallel to local slope contours, y = upslope/downslope direction perpendicular to the local slope contours or rows of cinders) measured in cm with stake #1 set at (0, 0) and downslope as the positive y-axis direction.
[2] No measurable movement from July 1992 position (in parenthesis).
[3] Unable to relocate or find painted cinder.
[4] Anomalous movement – cinder not used in statistical calculations.

Grid 2. Location: south crater rim (facing south) on Black Bottom Crater at an elevation of 1902 m.
Emplaced: July 2, 1992
First field survey: August 4, 1992
Second field survey: August 16, 1994

Cinder	Aug. 1992 position[1]	Distance moved (cm)	Direction moved (deg.)	Aug. 1994 position	Distance moved (cm)	Direction moved (deg.)
1	7, 19.5	10.0	197	–[3]	–	–
2	20, 12	2.0	180	13, 28	19.3	201
3	(30, 10)[2]	0	–	31.5, 15.5	5.7	165
4	45.5, 10	5.5	270	61.5, 48.5	44.1	151
5	50, 5.5	4.5	0	40, 54.5	45.6	193
6	(60, 10)	0	–	61, 17	7.1	172
7	(70, 10)	0	–	73.5, 59	49.1	176
8	(80, 10)	0	–	82, 15.5	5.8	160
9	88, 22	12.2	189	84.5, 49	39.4	188
10	(100,10)	0	–	101, 25.5	15.5	176
11	7.5, 22	3.2	231	–	–	–
12	(20, 20)	0	–	–	–	–
13	(30, 20)	0	–	29.5, 33.5	13.5	182
14	(40, 20)	0	–	39, 30.5	10.6	185
15	50, 21	1.0	180	–	–	–
16	63, 24	5.0	143	59, 30	10.0	186
17	(70, 20)	0	–	–	–	–
18	(80, 20)	0	–	86.5, 34.5	15.9	156
19	(90, 20)	0	–	89, 25	5.1	191
20	(100, 20)	0	–	99.5, 28.5	8.5	183
21	8.5, 31	1.8	236	21.5, 37.5	13.7	123
22	(20, 30)	0	–	28, 43	15.3	148
23	27, 33	4.2	226	28.5, 37.5	7.6	191
24	40.5, 29	1.1	27	55, 45	21.2	135
25	44, 46	17.1	201	40.5, 61	32.4	197
26	64, 31	4.1	103	66, 38.5	10.4	145
27	72.5, 33	3.9	140	68.5, 53.5	23.6	184
28	84.5, 25	6.7	42	90.5, 67	38.5	164
29	91.5, 29	1.8	56	81.5, 65.5	36.5	193
30	98, 35	5.4	202	92.5, 94	64.4	187
31	(10, 40)	0	–	27, 58	24.8	137
32	20, 41.5	1.5	180	24.5, 61.5	22.0	168
33	33, 48	8.5	159	23.5, 76.5	37.1	190
34	38, 40.5	2.1	256	39.5, 54.5	14.5	182
35	50, 37	3.0	0	44.5, 91.5	51.8	186
36	64, 40	4.0	90	66, 52	13.4	153
37	69, 42	2.2	207	10, 72	68.0	242
38	–	–	–	76.5, 53	13.5	195
39	91.5, 41	1.8	124	–	–	–
40	(100, 40)	0	–	–	–	–
41	10, 54	4.0	180	13.5, 66.5	16.9	168
42	(20, 50)	0	–	29, 75.5	27.0	161
43	30.5, 50.5	0.7	134	46.5, 109.5	61.7	164
44	(40, 50)	0	–	24, 89	42.2	202
45	(50, 50)	0	–	62.5, 61.5	17.0	133
46	51.5, 55.5	10.1	237	–	–	–
47	72, 50	2.0	90	69, 61.5	11.5	185
48	81, 49.5	1.1	65	77.5, 70	20.2	187
49	87, 54.5	5.4	214	81.5, 75.5	26.9	198
50	(100, 50)	0	–	98, 53.5	4.0	210

[1] Grid coordinates (x = direction parallel to local slope contours, y = upslope/downslope direction perpendicular to the local slope contours or rows of cinders) measured in cm with stake #1 set at (0, 0) and downslope as the positive y-axis direction.
[2] No measurable movement from July 1992 position (in parenthesis).
[3] Unable to relocate or find painted cinder.

Grid 3. Location: north crater rim (facing north) on Walker Lake cone (V3611) at an elevation of 2585 m.
Emplaced: July 21, 1992
First field survey: August 17, 1992
Second field survey: August 17, 1994

Cinder	Aug. 1992 position[1]	Distance moved (cm)	Direction moved (deg.)	Aug. 1994 position	Distance moved (cm)	Direction moved (deg.)
1	10.5, 22	12.0	178	–[3]	–	–
2	34, 42	34.9	156	–	–	–
3	32.5, 12	3.2	129	–	–	–
4	43.5, 21	11.5	162	–	–	–
5	49, 17	7.1	188	–	–	–
6	77, 91	82.8	168	–	–	–
7	72, 13.5	4.0	150	72, 98	88.0	179
8	75.5, 31.5	30.7	188	53, 191	183.0	188
9	–	–	–	–	–	–
10	100, 41	31.0	180	–	–	–
11	13, 28.5	9.0	161	–	–	–
12	16, 29	9.8	204	–	–	–
13	(30, 20)[2]	0	–	–	–	–
14	41, 19	1.4	46	77, 163	147.7	165
15	55, 23	5.8	120	63, 88	69.2	169
16	62, 31	11.2	170	–	–	–
17	77, 34.5	16.1	154	–	–	–
18	–	–	–	–	–	–
19	90.5, 30.5	10.5	177	–	–	–
20	102.5, 24	4.7	148	50, 148	137.4	201
21	10, 30.5	0.5	180	65, 136	119.4	153
22	22, 38	8.2	166	34, 177	147.7	175
23	32, 37	7.3	164	–	–	–
24	45.5, 38	9.7	145	44, 104	74.1	177
25	51, 32	2.2	153	–	–	–
26	60.5, 62	32.0	179	–	–	–
27	73.5, 38	8.7	156	66, 172	142.1	182
28	82, 38	8.2	166	–	–	–
29	90, 34.5	4.5	180	30, 143	127.9	208
30	(100, 30)	0	–	120, 144	115.7	170
31	26.5, 79.5	42.8	157	–	–	–
32	24, 52.5	13.1	162	–	–	–
33	28.5, 43	3.4	207	45, 168	128.9	173
34	38.5, 42	2.5	217	–	–	–
35	50, 46.5	6.5	180	64, 143	104.0	172
36	58.5, 43	3.4	206	–	–	–
37	68, 31	9.2	347	–	–	–
38	81.5, 38.5	2.1	46	77, 123	83.0	182
39	92.5, 45	5.6	153	64, 92	58.1	207
40	94.5, 49.5	11.0	210	–	–	–
41	11, 55	5.1	169	–	–	–
42	23, 50	3.0	90	–	–	–
43	29.5, 66	16.0	182	–	–	–
44	41.5, 63	13.1	173	50, 138	88.6	174
45	53.5, 89	39.2	175	–	–	–
46	60.5, 47	3.0	10	–	–	–
47	71.5, 86.5	36.5	178	94, 168	120.4	169
48	82, 48	2.8	46	–	–	–
49	91.5, 52.5	2.9	149	–	–	–
50	100.5, 52.5	2.6	169	–	–	–

[1] Grid coordinates (x = direction parallel to local slope contours, y = upslope/downslope direction perpendicular to the local slope contours or rows of cinders) measured in cm with stake #1 set at (0, 0) and downslope as the positive y-axis direction.

[2] No measurable movement from July 1992 position (in parenthesis).

[3] Unable to relocate or find painted cinder.

Grid 4. Location: south crater rim (facing south) on Walker Lake cone (V3611) at an elevation of 2530 m.
Emplaced: July 21, 1992
First field survey: August 17, 1992
Second field survey: August 17, 1994

Cinder	Aug. 1992 position[1]	Distance moved (cm)	Direction moved (deg.)	Aug. 1994 position	Distance moved (cm)	Direction moved (deg.)
1	(10, 10)[2]	0	–	–[3]	–	–
2	(20, 10)	0	–	–	–	–
3	30, 12	2.0	180	37, 31	22.1	162
4	(40, 10)	0	–	–	–	–
5	(50, 10)	0	–	53.5, 24.5	14.9	166
6	(60, 10)	0	–	80.5, 22	23.8	121
7	72, 11	2.2	115	68, 30	20.1	186
8	(80, 10)	0	–	82, 15.5	5.8	160
9	(90, 10)	0	–	89.5, 22	12.0	182
10	(100, 10)	0	–	95, 31	21.6	193
11	(10, 20)	0	–	10.5, 25.5	5.5	175
12	(20, 20)	0	–	21.5, 32	12.1	173
13	(30, 20)	0	–	32, 24	4.5	154
14	39.5, 22	2.1	194	36.5, 36	16.4	192
15	(50, 20)	0	–	54.5, 34	14.7	162
16	(60, 20)	0	–	60.5, 54.5	34.5	179
17	(70, 20)	0	–	–	–	–
18	(80, 20)	0	–	85, 32.5	13.5	158
19	(90, 20)	0	–	91.5, 34.5	14.6	186
20	(100, 20)	0	–	91, 51.5	32.8	196
21	10, 39	9.0	180	8.5, 51	21.0	184
22	(20, 30)	0	–	19.5, 35	5.0	186
23	(30, 30)	0	–	32, 40	10.2	169
24	(40, 30)	0	–	54, 38	16.1	120
25	(50, 30)	0	–	61.5, 41	15.9	134
26	(60, 30)	0	–	68, 40	12.8	141
27	(70, 30)	0	–	–	–	–
28	(80, 30)	0	–	80.5, 46	16.0	178
29	(90, 30)	0	–	91, 41.5	11.5	175
30	(100, 30)	0	–	91.5, 45	17.2	210
31	(10, 40)	0	–	9, 48.5	8.6	187
32	(20, 40)	0	–	19, 46.5	6.6	189
33	(30, 40)	0	–	34.5, 49.5	10.5	155
34	(40, 40)	0	–	44, 50	10.8	158
35	(50, 40)	0	–	54, 48.5	9.4	155
36	(60, 40)	0	–	63.5, 48	8.7	156
37	(70, 40)	0	–	72, 47	7.3	164
38	(80, 40)	0	–	80, 45.5	5.5	180
39	(90, 40)	0	–	92.5, 59	19.2	173
40	(100, 40)	0	–	–	–	–
41	(10, 50)	0	–	13, 75	25.2	173
42	21, 53	3.2	162	18.5, 56	6.2	194
43	(30, 50)	0	–	29, 58	8.1	187
44	(40, 50)	0	–	45.5, 56	8.1	137
45	(50, 50)	0	–	–	–	–
46	(60, 50)	0	–	62, 57.5	7.8	165
47	(70, 50)	0	–	–	–	–
48	(80, 50)	0	–	80, 58.5	8.5	180
49	(90, 50)	0	–	–	–	–
50	(100, 50)	0	–	109, 78	29.4	162

[1] Grid coordinates (x = direction parallel to local slope contours, y = upslope/downslope direction perpendicular to the local slope contours or rows of cinders) measured in cm with stake #1 set at (0, 0) and downslope as the positive y-axis direction.

[2] No measurable movement from July 1992 position (in parenthesis).

[3] Unable to relocate or find painted cinder.

Landform Analysis, Vol. 2: 19–35 (1999)

Morphological and geological evidence for glaciotectonics in the area of the Saalian Glaciation, with special reference to Middle Poland

Halina Klatkowa

Institute of Quaternary Research, Łódź University, ul. M. Skłodowskiej-Curie 11, 90-505 Łódź, Poland

Abstract: The definition of glaciotectonics to include both the effects of glaciodynamic processes and the effects of glacioisostatic processes has been generally accepted. In Poland, the glaciotectonic style of the Wartian zone is one of the most distinctive features of the Saalian area; glaciotectonic symptoms are numerous in the western part, but disappear in the east. Such a division extends beyond the Polish borders – as continuous thrust ridges in the west and as a sporadic phenomenon in the east.

Attention is drawn to the relationships between geological structure and morphological features; they include such cases as: a direct reflection of thrusts in convex land forms, low-relief areas and relief inversion (in relation to the structure). Much importance has been attached to the marginal zone of the Łódź Plateau in Middle Poland.

This paper reviews the main genetic hypotheses which, usually, are based on the mechanism, rather than palaeogeographical conditions. Despite much discussion, several problems remain, e.g.:
– why, allowing that the mechanism was similar, are there such regional differences;
– why are the marginal zone of the Warta Stadial and the western part of Europe so well endowed in this respect;
– could palaeoclimatic conditions (different patterns of glaciation and deglaciation), and could postglacial vertical compensatory movements have conditioned the regional variation?

Key words: *glaciotectonics, relief, Saalian glaciation, Middle Poland*

The extent of the terms

Glaciotectonics, the term relating to processes and phenomena associated with the action of an ice sheet on its bedrock, is not always defined in the same way. Differences involve the acceptance or elimination of certain effects of that action, e.g. deformation structures which result from dead ice pressure. Contrary definitions may be cited as an example. Bartkowski (1968, 1974) proposed the term "glaciotectonics" in respect of "all disturbances of the structure of ice sheet material and its bedrock caused by dynamic pressure", where the term "dynamic pressure" is defined as "tangential pressure as a resultant of vertical static pressure of the ice mass and the horizontal "dynamic" movement of moving ice mass". Therefore, all diapiric effects, especially in dead ice conditions, cannot be glaciotectonic, as this author clearly points out (Bartkowski, 1974, p. 25). Jaroszewski (1985, p. 81) gave a radically different definition, according to which "glaciotectonic" is "deformation of ice sheet bedrock and material resulting from ice pressure and/or its friction with the bedrock". A similar opinion is expressed by Ruszczyńska-Szenajch (1983), who regards "glaciotectonics" as "the mechanical action of an ice sheet on the bedrock".

The author of the present work favours the view of Jaroszewski and Ruszczyńska-Szenajch. Thus, any further consideration of "glaciotectonics" in this paper will be based on their definitions, and the effects of differential ice pressure, such as diapiric movement of susceptible material in coarse-grained kame deposits. The latter are very often omitted from similar studies, but will be included in the present discussions.

By "the Saalian zone" (including the glaciotectonic section), the author means "the area in which glacial deposits of that age create the youngest Pleistocene member of a surface geological structure". This zone is E-W oriented, though gently deflected to the NE, and does not remain constant in width – several deep salients reach far to the south. The deepest of these indicates the presence of the Saalian ice sheet at the Moravian Gate, while shallower ones occur along the Vistula valley as far as the San river mouth and in the Nida Basin. As a generalisation, one might agree that