FROST HEAVING AND SURFACE CLAST MOVEMENT IN TURF-BANKED TERRACES, EASTERN GLACIER NATIONAL PARK, MONTANA

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FROST HEAVING AND SURFACE CLAST MOVEMENT IN TURF-BANKED TERRACES, EASTERN GLACIER NATIONAL PARK, MONTANA

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ABSTRACT

FROST HEAVING AND SURFACE CLAST MOVEMENT IN TURF-BANKED TERRACES, EASTERN GLACIER NATIONAL PARK, MONTANA

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Patterned ground consists of rocks, gravel, and soil, both sorted and unsorted, ordered on a landscape in the appearance of geometric shapes ranging from circles, polygons, nets, and stripes. Patterned ground occurs throughout the world in alpine, subarctic, and arctic regions. These places are increasingly threatened, through climate change, natural and human disturbance, and other disturbances in the surrounding environment of the patterned ground. In order to predict future responses and disturbance reactions of fragile periglacial environments such as patterned ground with active cryoturbation, movement rates need to be determined. Limited research concerning patterned ground in northwestern Montana has been published. In eastern Glacier National Park, patterned ground is evident on several alpine tundra sites; however, rates of movement are not known. Four questions were asked in this dissertation: (1) is surface movement occurring at selected study sites; (2) what are the temporal and spatial movements of individual surface clasts and markers; (3) do the surfaces of the study sites change in appearance over time; and (4) what is the rate of heave occurring at the study sites, temporally and spatially?

In eastern Glacier National Park, data were collected from three locations. Sites with microclimate differences were established at each of the three locations to compare and contrast the movement of surface objects over time. One location consisted of needle-ice pans, whereas the other two locations contained relict solifluction treads and risers. Data were collected from 105 markers, 90 nails, and 90 clasts. Observations of marker and clast sorting within turf-banked terraces occurred between 2003 and 2006, whereas observations of vertical heaving, using nails, occurred between 2005 and 2006. Field data and repeat photography techniques were used to measure and observe marker and clast position changes over time. Types of marker movement were classified into four types: lateral, vertical tilt, burial, and overturning. Clasts were classified by: lateral movement, vertical tilt, burial and rotation. Nails were measured in millimeters from the surface to the nail head.

The results of this research confirmed that the surface of needle-ice pans and relict solifluction treads were exhibiting active surface movement. Laterally, clasts moved more than markers at the same sites. Gravel and sediment burial occurred more frequently with markers than clasts. A majority of the sites changed little in surface appearance over time. Miniature sorted circles with fine sediment enclosed by gravel were observed at two sites in 2003 and another site in 2004 but the circles have since

been in a state of disorganization. Possible reformation of the miniature sorted circles at one of the sites was observed in 2006. Differential frost heaving, as evidenced by the heaving upwards of nails, is occurring at the 3 locations. Surface wash was determined to be a process operating at one location, whereas the other two locations were dominated by frost-related processes. Processes not eliminated as contributors or instigators of lateral and vertical surface movement were: desiccation cracking, differential frost heaving, primary frost sorting, and convective cells. Future research directions include the excavation of the study sites to determine the depth of movement and the monitoring of the subsurface temperature of the sites. Additionally, future research will include the assessment of changes in rate of surface movement in response to environmental changes.

CHAPTER ONE

INTRODUCTION

Predicting the reaction of processes active in a patterned ground environment to changing environmental conditions cannot be made without understanding the present activity of surface clasts. Created by processes operative in cold (alpine, subpolar, and polar) environments, periglacial patterned ground consists of clasts and soil, both sorted and nonsorted, ordered on a landscape in the appearance of geometric shapes ranging from circles, polygons, nets, steps, and stripes (Washburn 1956; Kessler and Werner 2003; Goudie 2004b).

In eastern Glacier National Park (GNP), Montana, pan-like depressions are located within needle-ice pans and relict solifluction treads and risers. These pans are generally less than 500 centimeters (cm) in length, and located in tundra above the alpine treeline (Butler and Malanson 1989, 1999; Butler *et al.* 2004). These areas are characterized by alpine tundra on upland slopes with turf-banked terraces comprised of non-vegetated treads and tundra-vegetated risers (Butler *et al.* 2004; Resler 2004). Baseline data are needed to describe the movement patterns and direction of clasts on the surface of these pans. Such data would contribute to a better understanding of the processes contributing to clast movement and the resulting patterns of this movement at these sites.

Objective

The objective of this dissertation was to investigate the surface movement of clasts and markers in a patterned ground environment within turf-banked terraces in order to understand microscale geomorphic processes and patterns occurring at two sites in eastern Glacier National Park, Montana. To fulfill this objective, the following questions were asked:

1. Is surface movement occurring at the study sites?
2. What are the temporal and spatial movements of individual surface clasts and markers?
3. Do the surfaces of the study sites, as a whole, change in appearance over time?
4. What is the amount of heave occurring at the study sites, temporally and spatially?

The first question was central to the success of the dissertation. If movement, i.e. changes in the appearance of the surfaces of study sites in GNP, does not occur, then the patterned ground features may no longer be active. If the sites are not active, then questions regarding movement within the sites would be unnecessary. Confirmation of surface movement occurred through the observations of markers and clasts, i.e. rocks larger than 1 centimeter (cm), located in the study sites.

The second question was concerned with patterns of temporal and spatial movement of individual objects. I wanted to understand the organizational process occurring on the surface of the study sites. By looking at the movement of individual objects, instead of considering each site as a single entity, I attempted to discover the relationship between existing clasts and fine-grained sediment, in addition to markers introduced to a pan. The temporal perspective was important because of the belief that frost action (defined in Chapter 2) was at least partially responsible for movement of surface materials in the pans. Knowledge of the spatial movement of clasts and markers was sought to better understand the geographic patterns, or lack thereof, of patterned ground features.

Changes in the appearances of the study sites over time were important to determine because the question focused on the overall changes in the surface appearance of the study sites. If rapid changes (i.e. over the course of weeks or months) in the surface appearance exist, implications for the time involved in forming and disbanded patterned ground features become apparent.

The final question seeks to connect surface changes to frost processes, specifically frost heaving. Nails pushed into the ground would help confirm frost-related processes were affecting the study sites. Surface wash and pan pooling are two other processes, in addition to frost processes, that could move pennies and clasts in pans. Nails observed heaved above the surface would assist in confirming that a type of process expanded and elevated, i.e. frost heaving, the surface had occurred. Heaving of the surface might be related to needle ice (see Chapter 2); therefore, the amount of nails that were heaved during this study (if at all) may be indicative of needle ice growth and the length of the needle ice filaments. Additionally, the amount the nails were heaved might be related to the amount the ground expands during a year or season.

CHAPTER TWO

LITERATURE REVIEW

Definition of periglacial

The term periglacial, using the root words of "peri" and "glacial", implies near or around the presence of glacial ice. However, geomorphologists now accept that the periglacial environment is not necessarily influenced nor controlled by glaciers (Washburn 1980; French 2000c; Worsley 2004). Łoziński (1909) is credited with first using the term "periglacial" to describe the conditions associated with mechanical weathering in the Carpathian Mountains of Europe (Washburn 1980). Later, Łozinski used the concept of a "periglacial zone" to delineate the region adjacent to Pleistocene-age glaciers, and to describe the geomorphic processes and climatic conditions existing in these regions (Selby 1985) with the climate controlled by the proximity to the ice sheets (Embleton and King 1968; Washburn 1980). Łozinski, in using the term periglacial zone, failed to quantitatively define the limits of the zone on the landscape. Restricting the use of this term to those areas near or adjacent to ice sheets or glaciers presented a problem, as it ignored regions without glaciers (either presently or in the geologic past) but with periglacial processes and landforms (Tricart 1969; Easterbrook 1999). For decades after Łozinski coined the term, scientists debated the use and meaning of periglacial; however, as noted by French (2003), Łozinski's creation of the idea of periglacial provided scientists with "the first unifying concept in periglacial geomorphology" (pg. 33).

Although arguments over its meaning were numerous, it was an idea that provided researchers with a way to classify landforms and processes connected to cold environments similar to environments where glaciers exist. Two main arguments arose: 1) what was a periglacial environment (Peltier 1950); and 2) was "periglacial" the correct term to be used for processes, landforms, and regions exhibiting frost-related phenomena (Washburn 1980)?

Peltier (1950) presented the concept of a periglacial morphogenetic region, relating climate to landforms (as a Davisian geographic cycle for periglacial regions). Peltier estimated his periglacial morphogenetic region to have mean annual temperatures of -15° to -1°C and mean annual precipitation of 127 – 1397 millimeters (mm). These climatic parameters did not remove the ambiguity of where the periglacial zone or environment existed as, almost 20 years later, Linton (1969) decried the lack of quantitative parameters. Price (1972) noted that maps illustrating the precise boundaries of periglacial environments were not available. The lack of parameters led to a wide array of landforms, processes, and regions called "periglacial" (Dylik 1964). Butzer's (1973) review of several landforms considered periglacial by different researchers in the high Drakensberg region of South Africa provides an excellent example of this problem.

Embleton and King (1968) reinforced applying the term "periglacial" to those areas directly next to glacial ice, but noted that the area may be of "indefinite width" (pg. 448) adjacent to glaciers. Sixty years after the term was first introduced, Péwé (1969) noted the continued lack of a singularly accepted definition of periglacial and the periglacial environment. Péwé (1969) and Davies (1969) both suggested refining the meaning of periglacial to specifically include permafrost (perennially frozen ground), although neither of their works explicitly stated they considered periglacial environments only to include permafrost-dominated areas. Dylik's (1964) view on permafrost and periglacial was simple: the presence of permafrost indicated a periglacial environment. However, in a periglacial environment, permafrost may not always be present. Tricart (1969) acknowledged criticism of the term "periglacial" for its inadequacy in describing the region where periglacial processes occur; however, Tricart supported the use of periglacial in referring to regions not necessarily containing permafrost or glaciers. Additionally, he encouraged the general use of the term instead of what he called "extreme interpretations" of periglacial (Tricart 1969, pg. 2).

Washburn's two seminal books (1973; 1980) on periglacial processes helped clarify the application of the term "periglacial" to processes, landforms, and environments; in addition to synthesizing the terminology of periglacial landforms. Washburn's definition of "periglacial" stated that glaciers were not responsible for the processes active in these regions (neither temporally nor spatially), and that the area was dominated by a cold climate (Washburn 1973, pg. 2; Washburn 1980, pg. 4). Added to Washburn's 1980 definition was the term "frost action" as a process; although the addition of frost action to a definition of periglacial was not original to Washburn. Thorn (1991) stated that Łozinski recognized the importance of freezing in a periglacial environment and frost action was mentioned by Péwé (1969); however, in Washburn's 1980 book, a specific process was now being identified as occurring in conjunction with a periglacial environment. Frost action was also mentioned by Price (1972) and French (1976b), both citing that frost action processes are dominant in a periglacial region. French's definition removed the necessity of temporal or spatial proximity to glaciers for periglacial processes to be active. Additionally, no unconditional correlation exists between areas containing permafrost and the presence of frost action processes, thereby supporting the argument that the presence of permafrost is not required to be a periglacial environment.

Thorn (1991) provided a definition of periglacial geomorphology in his review of periglacial geomorphology as a subdiscipline. Slightly different than previously mentioned definitions because on its focus of processes and landforms, Thorn included ground ice (diurnal, seasonal, and perennial) as a process, and specified that the study of glaciers was not part of the periglacial sub-discipline. More recently, French (2000a; 2000c) and Worsley (2004) reinforced Washburn’s 1980 definition of periglacial environments by noting they are regions associated with cold climates that are not necessarily influenced by glaciers, and that the dominant processes active in these regions are related to frost. However, the lack of a consensus of a single definition continues, as Martini *et al*. (2001) noted, periglacial environments occur near glaciers.

The question of whether usage of the term “periglacial” should be continued has occurred at the same time as the modern evolution of the definition. In place of “periglacial”, Bryan (1946) advocated using “cryopedology” to refer to the new cold environment sub-science that began in earnest following World War II. He derived the term from “cryo” and “pedon” and included frost action and permafrost as part of this new science. Péwé (1969) noted other terms used in place of periglacial but none of those terms (e.g. “subglacial” and “sub-gelid”) were widely used in the literature. Other terms scientists substituted for periglacial included subglacial and cryonival. However, Dylik (1964), in his attempt to answer multiple questions about use and meaning of periglacial, clarified the definitions of both subglacial and cryonival, and in doing so, eliminated them as a possible replacement for periglacial. Decades later, Thorn (1991) noted an option of adopting other terms in place of periglacial since Łozinski's original meaning was no longer valid. However, recent definitions (French 2000a; Worsley 2004) indicate that the term "periglacial" is widely accepted and in use by cold-climate scientists. Though similar in appearance, the term "periglacial" should not be confused with the term "paraglacial". A paraglacial environment is a region having been directly adjacent to or under the climatic influence of glaciers (Ballantyne 2002). Additionally, a paraglacial environment also exists in deglaciated regions.

At present, whether a region is periglacial can be determined by the presence of either one of two criteria (French 1996b; Worsley 2004). The first criterion is that frost-related processes, such as freeze-thawing and seasonal freezing of the ground, are dominant and frequent. The second criterion is the presence of permafrost. Frost-related processes are likely to be present in regions containing permafrost; however, permafrost may not always be present in regions experiencing frost-related processes. This is especially true in alpine areas. These criteria fulfill the modern definition of periglacial by having either frost action or permafrost. In summary, periglacial environments are areas with frost-associated processes, either relict or active, in cold climates, not necessarily related to glaciers (either temporally or spatially).

Terminology

Frost action

The term “frost action” is used to describe processes occurring in periglacial environments and, therefore, to avoid confusion, is defined here. In the literature, the term “frost action” has two meanings, either as a specific weathering process or as a suite of processes including weathering by frost. First, as defined by French (2000b), it can refer to mechanical weathering occurring as water is subjected to freezing and thawing, either diurnally or seasonally, in rocks and soil. The force of the process is driven by the expansion of the water when frozen (to approximately 9% greater volume than its liquid state). This weathering concept is also called frost wedging in introductory physical geography and geomorphology textbooks (Easterbrook 1999; Christopherson 2006).

French (2000b) also made brief reference of the second, and more liberal, definition of frost action. Used in the definition of “periglacial” and for use in this dissertation, the term “frost action” refers to a suite of processes occurring in the ground in a cold climate. Better referred to as “frost action in the soils”(Washburn 1980), frost action is a collective term referring to multiple processes mutually related to the freezing/thawing concept, acting as one part of cold-induced weathering processes (Price 1972; French 1996b).

Freeze-thaw

Freeze-thaw refers to a cycle in which water changes states, between liquid and solid, both diurnally and seasonally. For some researchers (Washburn 1980), the freeze-thaw process is considered synonymous with frost action. A freeze-thaw cycle is not complete without a thawing process; therefore, this process is rarely important in high latitude climates where temperatures are consistently below 0°C. Regions of permafrost are affected by the freeze-thaw cycle but only in the thawing of the active layer during the summer months. The importance of the freeze-thaw cycle in periglacial environments cannot be understated. As noted above, when water changes states from liquid to ice, water expands in volume by approximately 9%. The expansion of water exerts pressure, both laterally and vertically, and is the underlying cause of several cryogenic processes. For instance, in frost wedging, the pressure exerted from the water expanding will break rocks apart. In frost creep, soil is slowly moved by the constant upheaval of ground during freezing and re-settled down slope upon thawing.

Frost heaving

In the periglacial environment, frost heaving is an important process related to the freeze-thaw cycle. Frost heaving pushes material both vertically and laterally, in response to the increase in volume from freezing water and from the formation of ice crystals in the soil (Price 1972). This process is effective at creating small humps in a road in the winter, later leading to cracked concrete upon thawing, and cracked foundations from the pressure exerted on building foundations (Williams 2004). Frost heaving can be active in all months of the year, with Matsuoka and Moriwaki (1992) recording over 50 frost heaving events during one summer in the Antarctic Mountains. Because material (including clasts and fine sediment) that is moved by frost heaving has different freezing properties, the ground does not freeze at the same temperature and time, nor does it hold the same amount of water and, therefore, will expand at different volumes. Consequently, unequal amounts of heaving occur across a surface. Also, the amount of heaving is influenced by insolation rates, vegetation, material, and aspect, leading to differential frost heaving and frost thawing (Price 1972). Although there is no dispute as to the occurrence of frost heaving, the relationship between duration, intensity and frequency and the resultant landforms is still being analyzed (Washburn 1980; Prick 2004). Two types of heaving identified by Williams and Smith (1989) are primary and secondary, with primary heaving influential near or above the frost line and secondary heaving influential at greater depths.

Cryoturbation

Cryoturbation is a process which occurs in regions experiencing frost action. As the root word (“cryo” = cold and “turbation” = churn) implies, cryoturbation is the cold, climate-related, churning of the ground, including soil and clasts (Goudie 2004a). Related to frost heaving (including frost-push and frost-pull mechanisms), freeze-thawing, and needle ice, cryoturbation occurs diurnally or seasonally and can be responsible for a large displacement of soil. Active cryoturbation, or the churning of the upper layer of soil and clasts caused by frost-related processes, can prevent establishment of vegetation, encourage erosion (Selkirk-Bell 2000, cited in Holness 2004), influence fluvial and chinook activity, and encourage or increase the rate of weathering processes. Sorted circles, a type of patterned ground discussed below, have been mentioned as a resultant landform of cryoturbation (French 1996b), but Van Vliet-Lamoë (1991) also associated nonsorted circles, nets, and polygons with cryoturbation.

Needle ice

Occurring at or just beneath the ground, needle ice is the term that refers to the growth of ice crystals in long filaments (hence the term “needle”) arranged (usually) perpendicular to the surface (Washburn 1980; French 1996a). The phenomenon has been associated with the formation of small-scale, or under 1 meter (m), sorted patterned ground features (Mackay and Mathews 1974; Washburn 1980; French 1996a), in addition to being instrumental in the occurrence of frost creep (Embleton and King 1968; Price 1972; Matsuoka 1998), stream bank erosion (Lawler 1993; Grab 1999, 2004), and solifluction (Troll 1958). Additionally, needle ice is a factor behind the churning of soil by frost processes (i.e. cryoturbation). Price (1972) attributed needle ice to doing the most geomorphic work through frost creep; however, research quantifying the amount of geomorphic work completed by each process associated with needle ice has yet to be completed.

The direction of needle ice crystal growth can be affected by wind, sunlight, and gravity (Washburn 1980; French 1996a; Grab 2004). Needle ice, often the underlying cause of frost heaving, causes small gravel and soil to be pushed towards the surface as the ice filaments grow in length (Fairbridge 1968b). The length of needle ice varies from millimeters to centimeters with Troll (1958) and Grab (2004) reporting on needle ice reaching over 40 cm after several days. Fairbridge (1968a) reported average lengths of 2 to 10 cm long. Needle ice, once formed, can last for days to weeks, provided the ground temperature does not rise above freezing.

Needle ice is found in regions with diurnal temperatures reaching below freezing, including tropical to sub-arctic alpine regions, coastal areas, and in subpolar regions where temperatures reach above freezing (Price 1972; Grab 2004). Tricart (1969) emphasized that needle ice needs an environment that has sudden freezes occurring in moist ground, whereas Price (1981) noted that needle ice needs a clear, calm night with freezing temperatures to form.

In Lawler's (1988) extensive review of the geographic distribution of needle ice research, previous studies in North America covered both mountainous and non-alpine regions (e.g. Indiana, eastern Oregon, Ohio, and Georgia). North American alpine areas that have been the site of needle ice research includes the White Mountains, California (Beatty 1974), the San Francisco Mountains, Arizona (Haasis 1923), the Beartooth Mountains in northern Wyoming and southern Montana (Johnson and Billings 1962), and the Indian Peaks region, Colorado (Fahey 1973, 1974).

Other conditions needed for needle ice development vary according to different researchers. Outcalt's (1971) list of 3 parameters crucial for needle ice development has been widely disseminated by several scientists (e.g. Washburn 1980; Lawler 1988; Grab 2004). Outcalt's (1971) requirements are: 1) surface temperature at or below -2°C, 2) high soil moisture resulting in low soil water tension; and 3) water migrating to the freezing front at a sufficient rate.

Internationally, needle ice has many interchangeable terms, including pipkrake (Swedish), the most popular alternative to the term "needle ice"; but also, mush frost (USA), kammeis (German), and shimobashira (Japanese) (Troll 1958; Washburn 1980).

Lawler (1988) identified four gaps in needle ice research. First, although many qualitative observations (cf. Mackay and Mathews 1974; Pérez 1987; Grab 1999) are available reporting the amount of sediment displaced by needle ice, quantitative studies concerning the growth rates of the filaments are rare, probably due to the timing involved in measuring growth rates (i.e. early morning) and the scale of the phenomenon (small to microscopic). Second, Lawler noted the lack of data describing the frequency of needle ice event in climates experiencing frost. For example, Matsuoka (1998, pg. 401) observed soil movement along transects over three years with automated monitoring, but only reported a "high frequency" of diurnal freeze-thaw events (capable of producing needle ice) during two months of the year. Grab (1999) provided some data, estimating that, annually, over 200 needle ice events occur in the Drakensberg region of South Africa. In North America, annual events have been reported with much lower frequencies with Outcalt (1970, cited in Lawler 1988) reporting between 15 to 37 needle ice events per year in British Columbia. Third, Lawler highlighted the dearth of research which existed on the type of soil or the sediment composition needed for ideal needle ice growth. Silt is a major component in needle ice formation; however, the amount of soil between fines (sand, silt, and clay) and gravel necessary to produce needle ice is not known. French (1996a, pg. 334) ascribed "wet, silty, frost susceptible soils" to intense needle ice. A minimum ten percent clay/silt is necessary for needle ice to develop fully according to Grab (2004); whereas Meentemeyer and Zippin (1981), in the laboratory, found that needle ice needed 12 to 19% clay/silt content to change from soil water to ice. The final gap described by Lawler was the lack of research explaining the processes occurring between sediment and needle ice and, additionally, the processes occurring in frost creep produced by needle ice.

Needle-ice pans

Needle-ice pans are depressions located in alpine environments, although the pans are not necessarily formed by needle ice. The exact cause of needle-ice pans is still under debate; however, needle ice is formed within the pans. Few research articles contain mention of needle-ice pans. Hasternath (1977) used the term to describe features in the Peruvian Andes. In the Venezuelan Andes, Pérez (1992b) defined the needle-ice pans he observed as 1 to 4 m in diameter, depressed from the surrounding tundra. The shape of the pans is generally circular or oval (Pérez 1992b; Grab 2002). The pans have an abrupt turf-banked edge surrounding it, producing a steep scarp 20 to 40 cm deep (Pérez 1992b). The pans are generally devoid of vegetation, attributable to needle ice growth disrupting the soil. Grab (2002) reported pan diameters of 3 to 6 m in the High Drakensberg, southern Africa. Pooled water in the pans or moist pans were typical of the needle-ice pans described by Grab (2002) and Pérez (1992b). Animal trampling and other animal-related disturbance of the vegetation and soil was a suggested cause of pan formation (Pérez 1992b; Grab 2002). Butler *et al.* (2004) noted the occurrence of needle-ice pans in GNP, but not excessive animal traffic through the research sites.

Solifluction

The term "solifluction" was first used by Andersson (1906) to describe landforms in the Falkland Islands, South Atlantic (Matsuoka 2004). Solifluction is a slow mass wasting process present on slopes experiencing freeze-thaw and/or frost heaving in periglacial environments; hence a cold climate is necessary for the process to occur, limiting the process to alpine and subpolar regions. French (2000d) separates the process from gelifluction, by limiting solifluction to those slopes experiencing seasonal thawing, whereas gelifluction has permafrost with an active layer thawing in the warm months. Solifluction can occur either when 1) soil, saturated and thawed, moves slowly down slope under the influence of gravity; or 2) soil is moved from frost heaving and resettled down slope from its original position (Matsuoka 2004). Landforms associated with solifluction include turf and stone-banked terraces (Billings and Mark 1961; Selkirk 1998; Malanson *et al.* 2002; Walsh *et al.* 2003a; Butler *et al.* 2004), lobes (Williams 1961; Fahey 1974; Smith 1986, 1987b; Matsuoka *et al.* 2005), and treads and risers (Fahey 1975; Malanson *et al.* 2002; Butler *et al.* 2004; Resler *et al.* 2005). Patterned ground is often found within solifluction-impacted regions. Benedict (1970) described patterned ground in a tread and riser environment on Niwot Ridge, Colorado. Other research observing patterned ground in treads and risers include Hansen-Bristow and Price (1985), who studied periglacial activity in the Olympic Mountains, Washington; Selkirk (1998; Selkirk-Bell 2000), who observed sorted circles on Macquarie Island, South Pacific; Smith (1986; 1987b), who recorded movement within miniature patterned ground on Mount Rae, Alberta, Canada; and Butler *et al.* (2004), who examined possible relationships between the upper limit of alpine treeline and turf-banked treads and risers in GNP. Troll (1958, pgs. 25-27) used the term “needle-ice solifluction” to explain the occurrence of solifluction occurring under the influence of needle ice versus the active layer of permafrost.

Turf-banked terraces

Landforms prevalent on low slopes (3-20°) in alpine and periglacial environments, turf-banked terraces are bench or stair-step accretions of soil, lacking obvious sorting, moving down slope [at a slow speed] (Benedict 1970; Gardner *et al.* 1983). The bench of the terrace is called the tread and is usually composed of gravel and stones. This area can exhibit sorted and nonsorted patterned ground. The riser, or face of the bank, is composed of vegetation. Dryas-banked terraces are a smaller-scale form of turf-banked terraces (Benedict 1970). Turf-banked terraces may form in a series of steps across a surface, with broad benches and relatively steep risers. Instead of having treads and risers across a slope, turf-banked lobes exhibit a tongue-like edge composed of turf vegetation at the end of the soil mass moving down slope. Stone-banked terraces and lobes have the same appearance as turf-banked features, but instead of turf, the risers are composed of stones. Benedict (1970) identified *intense* solifluction activity as the process responsible for turf-banked terraces and lobes whereas frost creep (the displacement of soil down slope as a result of needle ice) was responsible for stone-banked terraces and lobes. However, both soil creep and solifluction are attributed to turf-banked terrace formation (Washburn 1980; Hansen-Bristow and Price 1985; Butler and Malanson 1989; Walsh *et al.* 2003a). Most turf-banked terraces included in patterned ground research are inactive (e.g. Hansen-Bristow and Price 1985; Butler and Malanson 1989; Butler *et al.* 2004). Rates of movement down slope are not widely reported. In the arctic region of Canada, down slope movement rates of soil caused by gelifluction, and associated with terrace and lobe formation, have been measured at 28 to 31 mm per year (Washburn 1999).

The width of the treads and height of the risers varies between study sites globally. Caine (1968; 1981) observed particle movement on turf-banked terraces located on 3-12° slopes and a 1° slope in Tasmania. The height and width of the treads and risers were not reported other than noting the 1° slope had approximate 2 m risers, which was much shorter than risers on the higher slopes. At Mount Rae, southwestern Alberta, Canada, bare treads were 30 to 80 cm wide (Gardner *et al.* 1983). In GNP, stone treads averaged over 70 and 90 cm wide at two study sites (Butler and Malanson 1989). Two other study sites in GNP (Lee Ridge and Divide Mountain), turf-banked risers had a mean heights of 13.3 cm (Lee Ridge) and 14.4 cm (Divide Mountain). Mean widths at these study sites were 117.8 cm (Lee Ridge) and 117.7 cm (Divide Mountain) (Butler *et al.* 2004). In the Olympic Mountains, Washington, the turf-banked terrace risers averaged 57 cm with an average tread length of 2.7 m (tread width was not provided) (Hansen-Bristow and Price 1985). Selkirk's (1998) research on patterned ground on Macquarie Island was located on 3 to 6 m wide treads. Risers were approximately 1 to 2 m high. These terraces occurred on 5 and 25° slopes on the leeward side of the island. In the Hexriver Mountains, South Africa, slope angles ranged from 7 to 16° on slopes containing stone-banked lobes, relict solifluction lobes, and turf-banked steps (Boelhouwers 1995). The width of the turf-banked steps near Mt. Superior in the Hexriver Mountains averaged 1 m, whereas the height of the risers averaged 0.19 m.

Patterned ground

Unique landforms related to cold climates and frost processes occur within the periglacial environment. A periglacial landform classification using universally-used terms has yet to occur. Troll (1958) presented an early genesis and classification of patterned ground, other periglacial forms, and their environments. However, Washburn's series of works (1950; 1956; 1970; 1973; 1980) produced the seminal classification scheme for patterned ground that helped reduce the amount of overlap of terms for the same landform. Washburn's classification system provides a way to identify periglacial landforms before knowing the specific process that created the landforms, and is especially useful for describing relict landforms where the process ended hundreds to thousands of years ago.

Synthesized in Washburn (1956), patterned ground types are the bulk of periglacial landforms (other landforms include pingos, palsas, and blockfields or felsenmeer). Patterned ground includes a suite of forms and is defined as "the more or less symmetrical forms, such as circles, polygons, nets, steps, and stripes, that are characteristic of, but not necessarily confined to, mantle subject to intensive frost action" (Washburn 1956, pg. 824). The shape of these features in plan view, in order from most symmetrical to elongated, are: circles, polygons, nets, steps, and stripes (Table 1). The surface of the geometric form may be flat or raised above the surrounding surface, either along the edges or in the center of the landform. Other periglacial landforms with raised centers include frost boils (Wilkerson 1995), mima mounds (Black 1952), and hummocks or thufur (Fahey 1974; Matthews *et al.* 1998). Patterned ground can appear as sorted or nonsorted landforms, generally classified as such upon visual inspection. Sorting implies that the landform exhibits a distinctive progression from smallest to largest material size from the center outward, with the outer edges of the landform containing the largest clasts. Nonsorted features do not exhibit any order of clasts on the landscape, with

Table 1. Patterned ground research, sorted by form.

Form		Examples of research
Circles	Sorted	Corte (1963), Anderson (1988), Washburn (1989), Krantz (1990), Grab (1998), Kling (1998), Holness (2003), Cannone *et al.* (2004), Haugland (2004)
	Nonsorted (including stone, frost boils, earth hummocks, thufur, and earth mounds)	Vitek (1978), Ellis (1983), Mooers and Glaser (1989), Krantz (1990), Benedict (1992), Harris and Prick (1995),Wilkerson (1995), Grab (1998), Kozlowska and Raczkowska (2002) Cannone *et al.* (2004)
Polygons	Sorted	Clark (1968), Ballantyne and Matthews (1983), Ray *et al.* (1983), Smith (1986), Krantz (1990), Kruger (1994), Grab (1997), Kling (1998), Butler *et al.* (2004)
	Nonsorted (including stone and ice-wedge)	Black (1952), Corte (1963), Rapp and Clark (1971), Vitek (1983), Vitek and Tarquin (1984), Gleason *et al.* (1986), Krantz (1990), Schlyter (1992), Svensson (1992), Wilson (1995), Grab (1997), Wilson and Edwards (2004)
Nets	Sorted	Mitchell *et al.* (1966), Benedict (1992), Wilson (1995), Haugland (2004)
	Nonsorted (including stone)	Grabwell (1957), Goldthwait (1976)
Steps	Sorted	Boelhouwers (1995)
	Nonsorted	Rapp and Clark (1971), Grab (1998)
Stripes	Sorted	Clark (1968), Krantz (1990), Benedict (1992), Wilson (1992), Kozlowska and Raczkowska (2002), Matsuoka *et al.* (2003), Cannone *et al.* (2004)
	Nonsorted (including stone and vegetated)	Billings and Mark (1961), French (1974), Gleason *et al.* (1986), Noguchi *et al.* (1987), Butler *et al.* (2004)

different sizes of clasts and sediment mixed together. The shape of the landform tends to have a positive linear relationship to the slope: as slope increases, the shapes become increasing elongated, going from circles at low slopes through polygons, then nets to steps and stripes at the highest slope angle; although, Washburn (1980) noted nonsorted features may not follow this progression as predictably as sorted features. As implied with Washburn's definition, circles, polygons, nets, steps, and stripes are formed through frost processes and, therefore, limit patterned ground to polar, subpolar, and alpine tundra regions. Other landforms appear as geometric shapes but are not formed through frost processes nor do they exist in a periglacial environment. Other definitions of patterned ground include geometric shapes caused by processes other than frost action. Goudie (2004b) includes all types of surface features exhibiting geometric shapes, including gilgai (a landform whose process is attributed to the shrink/swell properties of clay), polygons on playas (formed from salt deposits or shrinkage from water evaporation), and Brouosse tigre or tiger brush (light and dark bands of vegetation) that give the impression of stripes on the surface (Goudie 2004b).

Individual types of patterned ground (i.e. a circle, polygon, or net) can be large, with sorted circles in Spitsbergen measuring over 3 m in diameter (Washburn 1980); however, patterned ground can be much smaller. Quantitative limits of the landforms considered "small patterned ground" was set at less than 1 m by Washburn (1980), but over the past 20 years, another quantitative classification based on the size of the very small patterned ground features has been recognized. Polygons measuring less than 9 cm were considered miniature in GNP by Butler and Malanson (1989). Stone stripes on Haleakala, Maui, measuring 3 to 13 cm in width, were considered miniature by Noguchi *et al.* (1987). On Mount Rae, Alberta, miniature stone polygons and nets averaged 12 cm in diameter (Smith 1986). Features called micro-polygons, instead of miniature polygons, measured approximately 20 cm by Krantz (1990). Widths of miniature stripes in the Venezuelan Andes were less than 12 cm (Pérez 1992a). Quantitative parameters defining "miniature patterned ground" were given by Wilson and Clark (1991), who specified miniature patterned ground have a "mesh diameter or stripe width not exceeding ca. 20 cm" (pg. 369). These parameters have been adopted by other researchers, with two articles on miniature patterned ground (Grab 1997; Butler and Malanson 1999) citing Wilson and Clark's specifications to be considered miniature. Hall (1994) also used those dimensions in his observations on sorted stripes in the South Shetland Islands, off the coast of Antarctica. Ballantyne (1996, pg. 410) expanded Wilson and Clark's definition, when he reported on sorted nets in Scotland less than 20 cm in width, by specifically mentioning all types of pattered ground (removing the term "mesh"): "Miniature frost-sorted patterned ground take the forms of circles, nets, polygons and stripes less than 0.2 m in width".

Patterned ground processes

Frost action and related processes (freeze-thaw and frost heaving) are necessary for periglacial activity. However, the specific processes responsible to develop patterned ground remain a subject of debate. Washburn (1956) identified nineteen possible mechanisms responsible for the formation of patterned ground; by 1980, Washburn (1980) had modified these process by categorizing them into two basic origin types: surface cracking-essential processes and non-essential surface cracking processes, both of which are linked to sorted and nonsorted patterned ground landforms (Table 2). The cracking of the surface is caused by the contraction and expansion of the ground in relation to active processes. The processes listed in Table 2 are also associated with the modification of patterned ground once formed; however, the process responsible for the formation of patterned ground may not be the same process actively modifying patterned ground after formation (Washburn 1980). Consequently, it is often difficult to ascertain why patterned ground exists (either in relict or active form).

Researchers have begun focusing on convective cells active in the subsurface as a dominant process in patterned ground (Ray *et al.* 1983; Gleason *et al.* 1986; Kessler and Werner 2003); however, convective cells are commonly associated with sorted patterned ground rather than nonsorted. Malanson *et al.* (1990; 1992) suggested that, as a continuation of the theory that convection cells in the mantle (Julian 1990; Kellogg and Turcotte 1990) may be connected to chaos theory, patterned ground convection cell processes are linked to deterministic chaos theory. In cold climates that experience seasonal and diurnal freezing temperatures, freeze-thawing, cryoturbation, and frost heaving should be expected and have been associated with influencing nonsorted features (Fahey 1975; Washburn 1980; Grab 1998). Differential frost heaving (uneven surface heaving) may explain why heaving rates of nails and dowels may vary across a nonsorted surface (Van Vliet-Lamoë 1991; Matsuoka *et al.* 2003). Differential frost heaving could also be responsible for clasts moving as the surface expands at different rates, causing sediment on the edges of the expansion to fall to the side or be buried by other sediment.

Table 2. Washburn's (1980) list of patterned ground formation processes.

Cracking essential	Non-essential cracking	
Desiccation	**Differential:**	Frost heaving
Dilation		Mass-wasting
Frost action along bedrock joints		Thawing and eluviation
Permafrost	**Non-differential:**	Mass displacement
Salt		Primary frost sorting
Seasonal frost		Rillwork
		Salt heaving

Desiccation cracking is the result of soil drying and contracting (Washburn 1980). It is associated with small and miniature patterned ground, both sorted and nonsorted features. Silt and clay needs to be present for desiccation cracking (Washburn 1980); however, the amount of either silt or clay needed for activity has not been specified. Development of sorted polygons from existing nonsorted polygons was attributed to desiccation cracking in a recently deglaciated environment in Norway (Ballantyne and Matthews 1983).

Seasonal frost cracking has also been associated with sorted and nonsorted landforms (Washburn 1980). Unlike desiccation cracking, silt and clay do not need to be present; however moisture is required. Frost cracking begins each fall, and upon the ground thawing in the spring the cracks may disappear (Washburn 1980), making confirmation of the process difficult.

Research methods

Research methods used to study patterned ground have changed little over the past 40 years. French (1976a) noted the use of photographs and surface markers by researchers studying patterned ground. Vitek (1978; 1983; Vitek and Tarquin 1984) studied stone polygons, earth mounds, and stripes in Colorado over several years, using morphometric data collected in the field and repeat photography. In Spitsbergen, large sorted circles have been studied by Hallet and Prestrud (1986), using descriptive observations. They have reported on the vertical motions and lateral surface displacement (using matches placed into the ground), in addition to the subsurface organization of sorted circles by excavating an area. In a more invasive method, horizontal bars were placed across a sorted circle and joined on either side to poles placed into the ground. The amount of frost heaving and post-heave settlement was then observed by inserted rods hanging below the horizontal bars (Kling 1997). A similar apparatus, a bedstead, was used by Fahey (1974) to study frost boils on Niwot Ridge, Colorado. A heavograph, an automated monitoring device used to measure frost heave, was also installed on Niwot Ridge (Fahey 1973). Selkirk (1998) determined lateral movement rates in sorted polygons over time by using painted rocks and pegs. Morphometric data were collected from 1,200 sorted circles on Marion Island, near Antarctica, to report on the characteristics present in patterned ground in a subantarctic region (Holness 2003).

Markers and surface clasts

Using painted clasts, tinfoil, and markers, on the surface of patterned ground, to observe change is a well-established method in patterned ground research. Over 45 years ago, painted stones were placed on stone nets and stripes in an alpine region of Malborough, New Zealand, to observe changes in their lateral position over a year (Gradwell 1957). Caine (1968; 1981) used painted stones in Ben Lomand, Tasmania, to observe movement of sediment in turf-banked terraces. In miniature polygons and nets on Mount Rae, Alberta, painted stones and grids of marked stones (which replaced the original stones) illustrated movement over an eight-year period (Smith 1986). Benedict (1992) painted lines in sorted nets to determine the types of movement occurring on Niwot Ridge, Colorado. Activity within the sorted nets moved stones within the painted lines, offsetting the original lines due to freeze-thawing. In earlier research, Benedict (1970) painted individual stones within sorted stripes, using a horizontal wire stretched across the stripe to observe position movement. In the Venezuelan Andes, glass marbles were used, in concert with painted gravel, to observe movement within miniature sorted stripes, both on the surface and in the subsurface (Pérez 1992a). The site was re-visited and field measurements taken 5 years after placement. A line of painted clasts placed in a miniature sorted net was studied over 18 months to document lateral movement (Ballantyne 1996). Shallow freezing was attributed to moving clasts within six weeks after first placed. Selkirk (1998) also used painted stones on vegetation-banked terraces on Macquarie Island, to observe movement periodically over 2 years. She confirmed active movement of clasts within the terraces during the first post-placement field visit. In the southern Japanese Alps, nine 4 cm wide lines, ranging from 230 to 875 cm in length, were painted on stone-banked lobes to study surface creep, and observed over a 3-year period with automated monitoring (Matsuoka 1998). The study sites were dominated by diurnal freezing and thawing. Matsuoka reported a near steady annual movement rate over the 3 years of observation.

Painted transects and markers were used in the White Mountains, California, to observe changes in frost boils and sorted polygons (Wilkerson 1995). Coins were placed 10 cm apart using a grid to observe the rotational and lateral movement occurring on the surface of frost boils. Overturning, burial, tilting, and lateral movement of markers were observed after 10 months (following a winter and a spring). Grab (1999) painted clasts reflective of the same size as the existing coarse fragments and placed them along a transect adjacent to a stream bank to measure down slope movement. After nine weeks, the movement of the clasts was measured. Clasts were found buried, with one clast buried 15 mm.

A disadvantage of note in using painted clasts and markers is the overestimation of movement during the initial period of observation (Caine 1981); however, observing the movement of clasts already on the surface and left untouched would alleviate overestimation concerns. In the Bolivian Andes, clasts painted different colors were used in three different sections of a stone-banked sheet to observe movement over varying lengths of time (Francou and Bertran 1997). In that study, the authors reported a comparatively high rate of movement after the first six months in all the plots except one, with movement rates declining after increasingly amounts of time passed since initial placement.

Nails and dowels

Nails and wooden dowels have been used to study vertical and lateral displacement due to frost action in periglacial environments. Hallet and Perstrud (1986) used wooden markers to note lateral displacement in Spitsbergen, reporting that thawing produced a mean displacement of a few millimeters and that the displacement was noticeable 1 year after placement. Aluminum and wooden dowels were used in a 3-year study of frost heaving on Cornwallis Island in the Canadian Arctic (Washburn 1989). In order to measure heave, leaning, and lateral displacement, Washburn placed aluminum dowels 200 mm into the ground, whereas wooden dowels were placed 100 mm into the ground. Average heaving was 61 mm for the wooden dowels and 45 mm for the aluminum dowels. Wilkerson (1995) used wooden dowels and common nails placed in random, stratified random, and grid patterns in frost boils to measure heaving and displacement for 10 months. In the High Drakensberg area of southern Africa, wooden pegs were inserted into thufur, or frost-induced hummocks, and in areas adjacent to the thufur at varying depths (Grab 1998). After 3 months, heaving was noticeable and some pegs were not located. Holness (2004) also used wooden dowels, placed in four study sites at different altitudes, in his research on Marion Island. Dowels were placed into the ground at 50, 100, 150, and 200 mm depths. Measurement of dowel heights was completed 10 to 12 months later. Heave rates decreased for dowels placed at greater depths with a mean heave rate of 25 mm for dowels placed 50 mm into the ground and a mean heave rate of 1.9 mm for dowels placed 200 mm deep (results are from a study site at the same altitude). Study sites located at higher altitudes produced dowels that had been heaved more than at sites residing at lower altitudes. All the dowels placed at the highest altitude study were heaved with average rates exceeding 50 mm (dowels placed at 50 mm depths had a mean heave of 50 mm).

A disadvantage of using dowels is that they do not indicate any settling that may occur after heaving. Additionally, without measuring the amount of lift experienced by dowels daily, it can only be assumed that the amount of vertical heaving occurred over the season or annually, when it is possible that heaving occurred on a much shorter time frame.

Repeat photography

Repeat photography is a method of comparing images of the same landscape to discern any changes. Photographs of US landscapes were first taken in the mid-1800s but were rare until the end of the 19th century (Trimble and Cooke 1991). Photographs are a static record of a landscape at a specific point in time (Munroe 2003). Therefore, repeat photography is a technique in geomorphic research suited for projects involving short time scales of fewer than 125 years. National parks have been the source of multiple studies using repeat photography, mainly due to two reasons: 1) historical photographs exist of landscapes in national parks; and 2) as protected places, they provide an area usually free of human modifications, invaluable in research involving physical geography. In the United States, studies in national parks have included the Grand Canyon (Baars *et al.* 1994; Webb 1996); Lassen Volcanic (Williams 1928; Pérez 1998); Mount Rainier (Veatch 1969); Sequoia (Vankat and Major 1978); Rocky Mountain (Veblen and Lorenz 1991); Yellowstone (Meagher and Houston 1998); Yosemite (Heady and Zinke 1978; Vale 1987; Vale and Vale 1994; Stewart *et al.* 2002); and Glacier

(Johnson 1980; Butler 1985, 1994; Butler *et al.* 1994; Butler and DeChano 2001; Roush *et al.* 2007). International parks studied using repeat photography include Huascaran National Park in Peru (Byers 2000) and Waterton Lakes National Park in Canada (Cerney and Butler 2004).

The advantages of repeat photography are that it is “a simple, inexpensive, and elegant tool” (Swetman *et al.* 1999, pg. 1196). Classic methodological articles on repeat photography include Harrison (1974), Rogers *et al.* (1984), and Butler (1994). More recently, Kull (2005) provided a thorough review of repeat photography, including a discussion on temporal and spatial scale considerations in a project, and Hall (2002) included a discussion on re-photography and digital cameras. Problems with repeat photography vary with each project, and may include issues associated with the original photograph and information available about the data collected at the time the photo was taken, and about the photo itself. Using historic photographs requires previous knowledge of the photo point (where the photographer was standing at the time the photo was taken), the time of year and day of the original photo, and compatibility with the original camera equipment (Butler 1994; Munroe 2003). Often historical photographs were taken for their aesthetic appeal, rather than capturing a static record of the conditions of a place, and consequently information such as the year, season, exact location, and photographer may be unknown. Additionally, the quality of the photograph may have degraded. Repeat photography is also limited by distortions, misinterpretation, and incomplete knowledge (Rogers *et al.* 1984; Swetnam *et al.* 1999). Distortions in the original image may occur during development or reproducing. Also, similar distortions evident in early postcards (Sawyer and Butler 2006b), hand-coloring of photographs may change the image or color of features on the photograph. Misinterpretation can occur from distorted photographs or from seeing similarities or differences between landscapes on photographic pairs when none actually exist. Incomplete knowledge is common when using historical photographs, because not all the information may be available (i.e. time of year photo taken or a specific event occurred precipitating the photograph); additionally, not having a full understanding of the geomorphic, climatic, and biologic processes occurring at the site may cause misinterpretation.

Another limitation is that photographs used in repeat photography studies are typically oblique, distorting features and the scale of objects in the photos, limiting the type of data able to be obtained from the image (Avery and Berlin 1992; Kull 2005). Other limitations include those related to photogrammetric measuring and remote sensing classification of features (Table 3). Data collected from oblique photographs are usually qualitative, and involve comparing and describing the changes occurring, in addition to the overall observations of the changes that occurred between photographs (Vale 1987).

Table 3. Partial list of limitations in using repeat photography from a remote sensing viewpoint.

Limitations of repeat photography
Radial distortion
Radiometric resolution
Spectral resolution
Spatial resolution
Temporal resolution
Terrain distortion
Vertical and horizontal precision

Obtaining quantitative data from oblique photographs has been done in a few studies (Brink 1973; Webb 1996; Butler and DeChano 2001; Manier and Laven 2002; Cerney and Butler 2004; Wilmshurst *et al.* 2004; Roush *et al.* 2007). For example, Manier and Laven (2002) used 24 pairs of photographs to measure, both qualitatively and quantitatively, the change in aspen in the Colorado Rocky Mountains over approximately 90 years. Qualitatively, they identified vegetation disturbances and changes in the dominant vegetation cover types whereas quantitatively, they used landscape metrics (cover area, mean patch size, and number of patches) to calculate actual change.

Digital cameras have begun to replace film cameras as a research tool and offer several advantages over film cameras in repeat photography studies. First, the cost of purchasing and developing film is eliminated. Although there is cost associated with memory cards, it is a one-time purchase that is negated if the memory cards are reused. Limited only by memory card space, more photographs can be and are, taken without worrying about film cost. Viewfinders on digital cameras allow the photographer to compare images in the field, increasing the chance of getting an exact replicate of the original photograph. With the increase in resolution and zoom capabilities, digital cameras are able to produce better photographs than previously available. However, this is only an advantage when comparing photographs with similar resolutions. Additionally, software for digital images can change the color on photos, allowing distortions or enhancements of the original image. Hall (2002) listed three components associated with images produced from digital cameras that need to be taken into consideration in repeat photography studies. First, the camera’s resolution impacts the quality of the image and should be considered when working with multiple cameras on a re-photography study.

Second, the computer monitor (i.e. color settings, brightness, resolution) upon which the image is viewed can affect how the image is seen. Thirdly, if the image is projected onto a screen or printed, the quality and resolution are partially controlled by the device.

Compared to other topical research in physical geography (Table 4), periglacial studies have used repeat photography only on a limited basis. On Macquarie Island, aerial photographs taken 20 years apart revealed several changes on the landscape, including in the vegetation and erosion of sand (Selkirk and Saffigna 1999). The scale of this study is inappropriate for patterned ground research, but is very useful in other periglacial studies. Given the resolution of aerial imagery available today, patterned ground research is possible at the 1 m resolution; however, for long-term research, repeat aerial photography is limited by the lower resolution of older imagery. Using oblique photographs, observations of changes in stone polygons on the Blanca Massif in the Sangre de Cristo Mountains were reported using 5 sets of photographs taken over seven years (Vitek 1983). The conditions and sizes of frost boils and earth hummocks on Niwot Ridge, Colorado, was observed using 5 sets of photographs over 25 years (Benedict 1992).

Most repeat photography research takes place at a scale inherently larger than 20 cm (the scale of miniature patterned ground). Therefore, spatial scale is important when using repeat photography in patterned ground research, and is likely the reason repeat photography is not used more in periglacial studies. Because of the size of the features, repeat photography in lichen research requires similar resolutions and considerations as miniature patterned ground studies. Additionally, given the size of both miniature patterned ground and lichens, vertical photographs are possible using a hand-held

Table 4. Examples of research using repeat photography.

Research focus	Examples
Alpine treeline	Butler *et al.* (1994), Kullman (1997), Klasner and Fagre (2002), Munroe (2003), Elliott and Baker (2004), Cerney and Butler (2004)
Fluvial	Costa (1978), Graf (1978; 1979b), Williams and Wolman (1984), Traylor and Wohl (2000), Birkland (2002), Tiegs and Pohl (2005)
Geomorphic	Williams (1928), Graf (1979a), Butler (1985), Ives (1987), Butler and Malanson (1993), Butler and Malanson (1996), Webb (1996), Pérez (1998), Charlton and Merriam (2003)
Glaciers and related landforms	Harrison (1960), Price (1966), Veatch (1969), Post and LaChapelle (1971), Mottershead and White (1972), Foyer (1973), Johnson (1980), Chinn (1995), Kaser and Osmaston (2002), Moseley (2006)
Landscape change	Byers (1987; 2000), Works and Hadley (2000), Butler and DeChano (2001), Nüsser (2001), Kull (2005), Moseley (2006)
Periglacial	Vitek (1983), Benedict (1992), Selkirk and Saffigna (1999)
Riparian	Turner and Karpiscak (1980), Start and Handasyde (2002), Webb and Leake (2006)
Vegetation change	Bahre and Bradbury (1978), Heady and Zinke (1978), Vankat and Major (1978), Rogers (1982), Vale (1987), Kullman (1988), Veblen and Lorenz (1988; 1991), Hofgaard *et al.* (1991), Vale and Vale (1994), Veblen *et al.* (1994), Hutchinson *et al.* (2000), Manier and Laven (2002), Stow *et al.* (2004), Wilmshurst *et al.* (2004), Zier and Baker (2006)

camera. Originally documented through photographs in 1958, Brink (1973) re-photographed lichen growing in West Greenland in 1970. He was able to obtain thalli growth measurements to the millimeter using photographs. Foyer (1973) used a transparent grid (in mm) placed over lichen on rocks to photograph the original dimensions of thalli for future comparisons and growth rate calculations As with patterned ground, Foyer noted that the system was imperfect because the grid did not lay uniformly over the rocks, consequently distortions can be expected.

Rates of change

Annual and seasonal movement rates of surficial clasts in studies of patterned ground vary among previous research. Patterned ground is responsible for the displacement of large amounts of material each year, with stones along a transect moving 10 to 540 mm over 2-3 months in a subpolar region (Selkirk 1998); although Selkirk notes these movement rates were above average when compared to longer observation times at the same transects. In New Zealand, painted stones moved downhill at 25 to 76 mm per year for gentle slopes (2-5°) and 152 to 229 mm on steeper slopes (Gradwell 1957). Pérez (1992a) reported surficial movement in miniature sorted stripes of 2.9 to 9.5 cm yr^{-1}. Miniature sorted circles reformed over 5-6 weeks on an annual basis in southern Africa (Grab 1997), illustrating the impact of frost processes over a short time. The importance of seasonal frost heaving in Japan was presented in Matsuoka *et al.*'s (2003) study of sorted stripes and circles, reporting seasonal heave rates ranging from 11-30 mm for coarse material. Previous research on surface marker movement in the Venezuelan Andes reported rates of 603 mm yr^{-1} (Pérez 1992a), whereas rates of 36-600 mm yr^{-1} were reported from a subantarctic island (Holness 2004). Wilkerson (1995) noted a movement of 1 cm of material over 3 years in the White Mountains of California.

Glacier National Park research

A large body of research on the physical environments of GNP exists (Table 5). For this dissertation, specific areas of interest in previous research are alpine treeline, tundra/periglacial studies, and repeat photography studies.

In GNP, several studies have contributed to alpine treeline and tundra research (Figure 1). Resler (2004; Resler *et al.* 2005; Resler 2006) analyzed the conditions necessary for establishment of conifers as part of a project researching advancement of alpine treeline into the adjacent tundra. Resler's study sites in the GNP region were Lee Ridge, Cataract Creek Basin, and Divide Mountain (Figure 1), which are east of the Continental Divide. Relationships between conifer establishment and effective soil depth were determined not to be significant (Malanson *et al.* 2002). Butler *et al.* (2004) reported on the morphometric and topographic variables necessary for conifer establishment in the alpine tundra on solifluction treads and risers, noting that exfoliation at the base of treads made for a more hospitable environment for conifer establishment than risers. Schmid (2004) analyzed soils at the upper alpine treeline to observe variables related to changes in the surrounding environment at Lee Ridge and White Calf Mountain. Limited amounts of published research are available concerning alpine periglacial landforms and the geographic location of patterned ground in the GNP region. Bamberg and Major (1968) completed limited amounts of research on active patterned ground at Siyeh Pass in order to compare the results to their primary study area in the Big Snowy Mountains in central Montana. The primary objective of their research was to catalog and compare the vegetation and soils at three locations with similar geology. To measure terrace and soil movement, 90 cm steel rods were placed into the ground

Table 5. Partial list of GNP geomorphic and biogeomorphic-related research.

Research focus	Examples
Alpine treeline and tundra-related research	Alftine *et al*. (2003), Allen and Walsh (1996), Bekker (2005), Butler and Malanson (1989; 1999), Butler and Walsh (1994), Butler *et al.* (1994), Malanson *et al*. (2002), Butler *et al*. (2003), Butler *et al*. (2004), Cairns (1998), Cairns and Malanson (1997; 1998), Cairns and Waldron (2003), Cerney and Butler (2004), Geddes *et al*. (2005), Klasner and Fagre (2002), Resler (2004), Resler *et al.* (2004), Resler *et al.* (2005), Roush *et al*. (2007), Walsh *et al*. (1994), Walsh *et al*. (2003a), Walsh *et al.* (2003b)
Biogeography-related research	Bigler *et al*. (2001), Butler and Malanson (1995), Cairns (2001), DeChano and Butler (2002), Keane *et al*. (1999) Malanson and Butler (1984a; 1984b; 1986), Meentemeyer and Butler (1995; 1999)
Environmental and climate-related research	Butler and DeChano (2001), Dixon *et al*. (1999), Fagre *et al*. (1997) Hall and Fagre (2003), Pederson *et al.* (2004)
Glacier-related studies	Allen (1998), Butler (1989), Carrara (1993), Carrara and McGimsey (1981), Johnson (1980)
Mass movements	Butler (1979b; 1979a; 1980; 1985; 1986a; 1986b; 1987), Butler and Malanson (1985a; 1985b; 1990), Butler and Walsh (1990), Butler *et al.* (1992), Butler *et al.* (1998), DeChano and Butler (2001), Gao and Butler (1992), Oelfke and Butler (1985a; 1985b), Reardon *et al*. (2004), Sawyer and Butler (2006a), Walsh *et al*. (1990), Walsh and Butler (1997), Wilkerson (2004), Wilkerson and Schmid (2003)
Other natural hazard-related research	Butler and DeChano (1998), Butler and Malanson (1993; 1996), Butler and Wilkerson (2001)
Soils	Bamberg and Major (1968), Dutton and Marrett (1997), Karlstrom (2000), Nimlos and McConnell (1962; 1965), Schmid (2004)

at the upslope edge of the vegetation at Siyeh Pass in central GNP, in addition to two other sites in Montana. Compared to the other locations, the minimal movement of the rods at Siyeh Pass over 3 years resulted in the authors declaring Siyeh Pass to be "quite stable" (Bamberg and Major 1968, pg. 152).

Three types of patterned ground present in GNP were identified by Butler and Malanson (1989), through aerial imagery and field reconnaissance: 1) miniature sorted circles found on uplands with gentle slopes, 2) inactive alpine turf-banked terraces in upland areas, and 3) turf-banked terraces in sheltered cirques. The first type, miniature

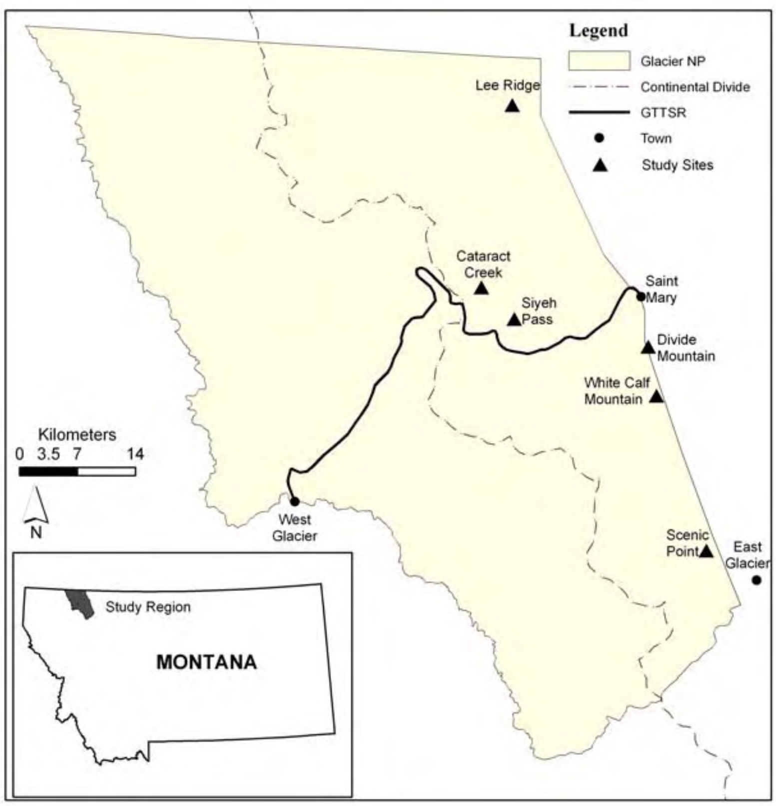


Figure 1. Relevant research study sites locations in GNP.

sorted features, ranged in diameter between 3 and 9 cm and contained coarse fragments. The second type, upland turf-banked terraces, was generally found in areas with northwest to northeast slope aspects. Average widths of the treads at these sites were 76.9 and 93.9 cm, respectfully, with the risers averaging 60.2 and 83.3 cm each. Cirque-floor patterned ground sites contain turf-banked terraces that are larger than the upland sites. Lichen development at the cirque-floor sites led the authors to suggest these sites are probably date from before the Little Ice Age (i.e. Late Neoglacial). Sixty-eight sites at five different areas in GNP were the focus of a study cataloging the characteristics of miniature patterned ground Butler and Malanson (1999). These sites were located east of the Continental Divide in GNP and ranged in elevation from 2174 m to 2266 m. Three different topographic regions were recognized in which miniature patterned ground was present: convex uplands, concave uplands, and on the sides of valleys. Among the sites, patterned ground was not found to be site-specific, i.e. similar patterns were found at various sites.

Repeat photography has been used previously to document changes in the physical environment in the GNP region. Butler *et al.* (1994) used repeat photography to examine changes at treeline in eastern GNP. A set of photographs taken one day apart were used to illustrate the effect in the appearance of a river after a major influx of sediment into a river from a debris flow (Butler and Malanson 1996). Butler and DeChano (2001) compared present-day photographs to 1930s era panoramic images taken from forest fire lookout posts to analyze landscape change. Photographs taken forty-six years apart were the basis of a study of changes in the alpine treeline in the McDonald Creek drainage region of GNP. That study concluded that that the ecotone is more abrupt between the forest and tundra biomes (Klasner and Fagre 2002). Expanding the interest area to the Waterton-Glacier International Peace Park, Cerney and Butler (2004) used repeat photography in three landscape views to analyze changes in the lower montane ecotone. At one site, the authors replicated a scene using 4 photographs taken over 79 years. Landscape-scale repeat photography using imagery separated by decades has been utilized in multiple studies in GNP, particularly on the alpine treeline region (cf. Roush *et al.* 2007). Up to date, micro scale geomorphic research utilizing repeat photography has been uncommon, in both international research and in GNP research. Additionally, research with repeat photography utilizing imagery only months apart has yet to occur on topics concerning the physical environment of GNP.

CHAPTER THREE

STUDY AREA

Glacier National Park

In the GNP region, patterned ground and other periglacial landforms located above alpine treeline are relatively undisturbed due to National Park Service management policies (largely in place since the GNP creation in 1910) and because of the region's remoteness. This situation creates an ideal setting in which to study alpine patterned ground. Previous research (Butler and Malanson 1989, 1999) identified areas, through field observations and aerial imagery, containing patterned ground in the GNP region. Additionally, recent research mentioned other areas in the GNP region containing patterned ground landforms (Walsh *et al.* 2003b; Butler *et al.* 2004; Resler 2004). Two locations, based on the above mentioned research, were chosen in eastern GNP to observe seasonal and annual changes in the miniature patterned ground surfaces (Figure 2). The locations have similar geology (Precambrian age rock) and surficial deposits (relict solifluction) (Table 6). Geomorphically, relict solifluction treads and risers are present and stable at both sites (Bamberg and Major 1968; Resler 2006).

GNP is dominated by glaciated landforms created during the Pleistocene epoch. These landforms include U-shaped glacial valleys, moraines, hanging valleys, cirques, and finger lakes. Physiographically, the region is part of the western Cordillera, which contains the northern Rocky Mountains (Fenneman 1931). The dominant geological structure in GNP is the Akamina Syncline, located in the central region of GNP with a north-south center axis, joining the Flathead Anticline on the western edge of GNP (Willis 1902; Fenneman 1931; Ross 1959). Two mountain ranges are located in GNP: the Livingston and Lewis Ranges. Both ranges are oriented northwest to southeast with the Livingston Range on the west side of the Akamina Syncline and the Lewis Range on the eastern side.

Two main climates exist in GNP. West of the Continental Divide, warm and moist Pacific air masses dominate the climate; whereas east of the Continental Divide, continental air masses from Canada and the Arctic region, that are drier and colder, are prevalent (Carrara 1993). Climate in eastern GNP is characteristic of a humid continental, short summer (Köppen Dfb) climate. The region experiences less precipitation and a greater range of monthly average temperatures (colder winters and warmer summers) than the western half of GNP. The nearest weather station to the study sites is Saint Mary, Montana (see Figure 2), at 1390 m elevation. From 1981 to 2005, mean monthly temperature at Saint Mary ranged from -5ºC in January to 17ºC in July and August (Figure 3). Average monthly minimum and monthly maximum temperatures ranged from a minimum of -9.7ºC in January to a maximum of 25.8ºC in August (Figure 4) (NCDC 2006). Diurnal freezing is possible during all months of the year, with mean monthly temperatures below freezing for 6 months (November to April) (Figure 4). Precipitation averages 677 mm per year, with the driest month (August) recording 43 mm and the wettest month (June) receiving 90 mm. Snowfall is possible in all months of the year.

Study sites

Between 2003 and 2006, several study sites (Table 6) at the two locations, Divide Mountains and Siyeh Pass, were established in pans on exfoliated treads, the surfaces of which are characterized by angular clasts and fine-grained sediments surrounded by tundra vegetation (for example, see Figure 11). At the first location, located at the base of Divide Mountain (elevation 2641 m) on the eastern edge of the Lewis Range, two different microclimate sites were established in the alpine tundra from 2003 to 2006 (Figure 5). A low ridge separates the sites, named Divide Mountain South (DMS) and Divide Mountain North (DMN). DMS is south-facing and has a low slope (1°). Each individual site at DMS is a needle-ice pan, or depression surrounded by alpine shrubs, contained mostly angular clasts with some sediment. DMN is north-facing and on a steeper (1-3°) slope. Solifiluction treads and risers are well-defined in this area. Pans within the solifluction treads in this area tend to have more fine-grained sediment than angular clasts. Given the steeper slope, drainage may be faster; however, with a northern slope, the DMN sites receives less sunlight and generally experiences cooler temperatures.

The sites at DMS are Sites 1(Figure 6), 2 (Figure 7), 3 (Figure 8), 4 (Figure 9), 5 (Figure 7), and 6 (Figure 10), established in 2003, 2003, 2004, 2006, 2006, and 2006, respectively. The sites at DMN are Sites A (Figure 11), B (Figure 12), C (Figure 13), and D (Figure 14), established in 2004, 2004, 2006, and 2006, respectively. The pans are dominated by nonsorted features, except at Site 1 (Hoofprint) and Site 2 (Deranged), where well-developed miniature sorted circles were observed during the initial site selection; however, the sorting was not maintained past the first visit to the site. Site 3

(Porkchop) also had miniature sorted circles present during the initial site establishment; however, the circles were less well-developed than the other sites. Each individual site has an oval to polygonal shape. High winds are experienced at both DMN and DMS sites and may remove snow from the pans during winter months. The area is accessible using a multi-use gravel road (for logging, utility and hiking trail access). Several off-road vehicles trails are visible from aerial photographs (Figure 5), but none travel through the individual sites. The immediate region around Divide Mountain shows little evidence of recent glaciation. Valley glacier landforms, such as lateral moraines, are visible from the sites; however, cirques and other high mountain glacial landforms associated with cirque glaciers are not present. The Divide Mountain sites were usually accessible for 3 of the 4 seasons (spring, summer, and fall).

Siyeh Pass (SP) is the second main study site, and was established in 2005 (Figure 15). SP is situated within the Lewis Range and east of the Continental Divide. The SP sites are located on relict solifluction broad treads and low risers that are oriented parallel to the slope (Figure 16). The selected pans are polygonal in shape (Figure 17, Figure 18). A few poorly sorted miniature circles were present in 2005. The site is on a narrower ridge (that forms a cirque headwall) than the Divide Mountain location. Below the SP sites is a U-shaped valley with Boulder Creek flowing north-eastward through the valley. Late-lying snow is visible in July and August near the solifluction treads and risers, whereas snow melts at Divide Mountain by late June. The slope faces east and is at a higher elevation than the Divide Mountain sites. The SP area shows extensive evidence of cirque and valley glaciation. Glaciated landforms surround the site, including cirques, U-shaped valleys, and nunataks. The SP sites are only accessible by a hiking trail; and, due to their high alpine location, the site is only accessible for a limited time each year, restricting field observations to only annual summer visits. The SP region was the site of an early study cataloging vegetation in alpine tundra. Bamberg and Major (1968) described placing nails in active frost boils at SP, in addition to spraying paint on entire study plots and rocks in a transect line to observe surface movement in the tread and riser environment of SP. From the photographs included in the above mentioned article, the sites I established were below the area used in their study.

Climatically, for Divide Mountain, the region around Saint Mary experiences chinooks that have the potential to affect the Divide Mountain sites, whereas the SP region is sheltered and less likely to experience chinooks. Hall and Fagre (2003) reported an increase of 1.66°C in the mean annual temperature from 1910 to 1980. Since 1980, average temperatures in GNP have increased a small amount, primarily evidenced in the winter mean temperature (Hall and Fagre 2003). Inactive solifluction terraces located east of the Continental Divide (Butler and Malanson 1999) suggests a colder climate once existed, reinforcing climate records that show climatic warming.

Geologically, both Divide Mountain and SP have sedimentary rocks from the Belt Supergroup, which formed during the Precambrian Era (Williams 1992). The SP region also contains some metamorphic rock (argillite, gneiss, schist, and quartzite) (Bamberg and Major 1968; Dutton and Marrett 1997) in addition to the dolomites, limestone (stromatolitic and oolitic), and quartz arenite from the Helena formation (Williams 1992). The Divide Mountain region is dominated by Altyn limestone (Carrara 1993) and is on the eastern edge of the Lewis Thrust Fault. The fault creates an area of unconformity where Precambrian rock was pushed over Cretaceous rock (Willis 1902). The fault extends along the eastern side of the Lewis Range from Alberta to Montana (Billings 1938). Slopes along the fault are prone to landslides as a result of the weak Cretaceous shales underneath Altyn limestone (Oelfke and Butler 1985a; Rockwell 2002).

For the Divide Mountain sites, Dutton and Marrett (1997) identified the soils in eastern GNP as bedrock soils rather than deposits from glacial or alluvial activity. The soils are broadly classified as Lithic Cryochrepts and experience intense frost-related processes (Dutton and Marrett 1997). Soils in the SP area were identified as part of the Montana Ptarmigan Series by Nimlos and McConnell (1962; 1965). Ptarmigan Series soil forms on argillite, gneiss, schist, and quartzite (Nimlos and McConnell 1962), and is a slightly acidic (pH 5.0) soil that is well-drained (Bamberg and Major 1968), whereas soil derived from limestone would be more alkaline. At the SP site, a shallow trench (ca. 20 cm deep and 15 cm wide) dug near the study sites and void of vegetation, exposed stony soils with very little horizon development. *Dryas octopetala* is the dominant vegetation at both SP and Divide Mountain (Bamberg and Major 1968; Butler *et al.* 2004; Resler *et al.* 2005). Conifers are visible from the Divide Mountain sites, primarily as krummholz (Figure 5), at the upper limit of alpine treeline. Near the DMN sites, krummholz grow within approximately 100 m of the site. Some tree fingers extend up the slopes of Divide Mountain to the north of the sites. Near the DMS sites, the upper limit of the alpine treeline is approximately 75 m south-southeast of the study sites. At SP, the study sites are well above treeline and no conifers are present on the slopes near the sites (Figure 15).

Disturbances to the sites during the study period were minimal. Possible disturbances to both study sites included humans, ungulates, and small mammals.

Interference from mass movements was minimal as both SP and Divide Mountain sites were located away from steep slopes. I was concerned that humans and animals could move or remove markers; additionally, animals could do substantial damage to the pans through digging or trampling. Other possible damage included wildland fires; however, the extent of natural disturbance from fires burning through a study site would have been limited to the loss of surrounding vegetation. The only disturbances observed during the study period were a set of three ungulate hoof prints (either Rocky Mountain elk, *Cervis Canadensis*, or deer, *Odocoileus* sp.) through a small section of Site 1 (now colloquially named Hoofprint) at DMS. Off road tire tracks were found near the DMS sites but not near enough to disturb the sites. The Red Eagle wildfire, which started July 28, 2006 near Saint Mary, Montana, burned into krummholz within meters of the DMN sites but no trampling or other human-related fire-fighting disturbances were found during a visit to the sites seven weeks post-fire.

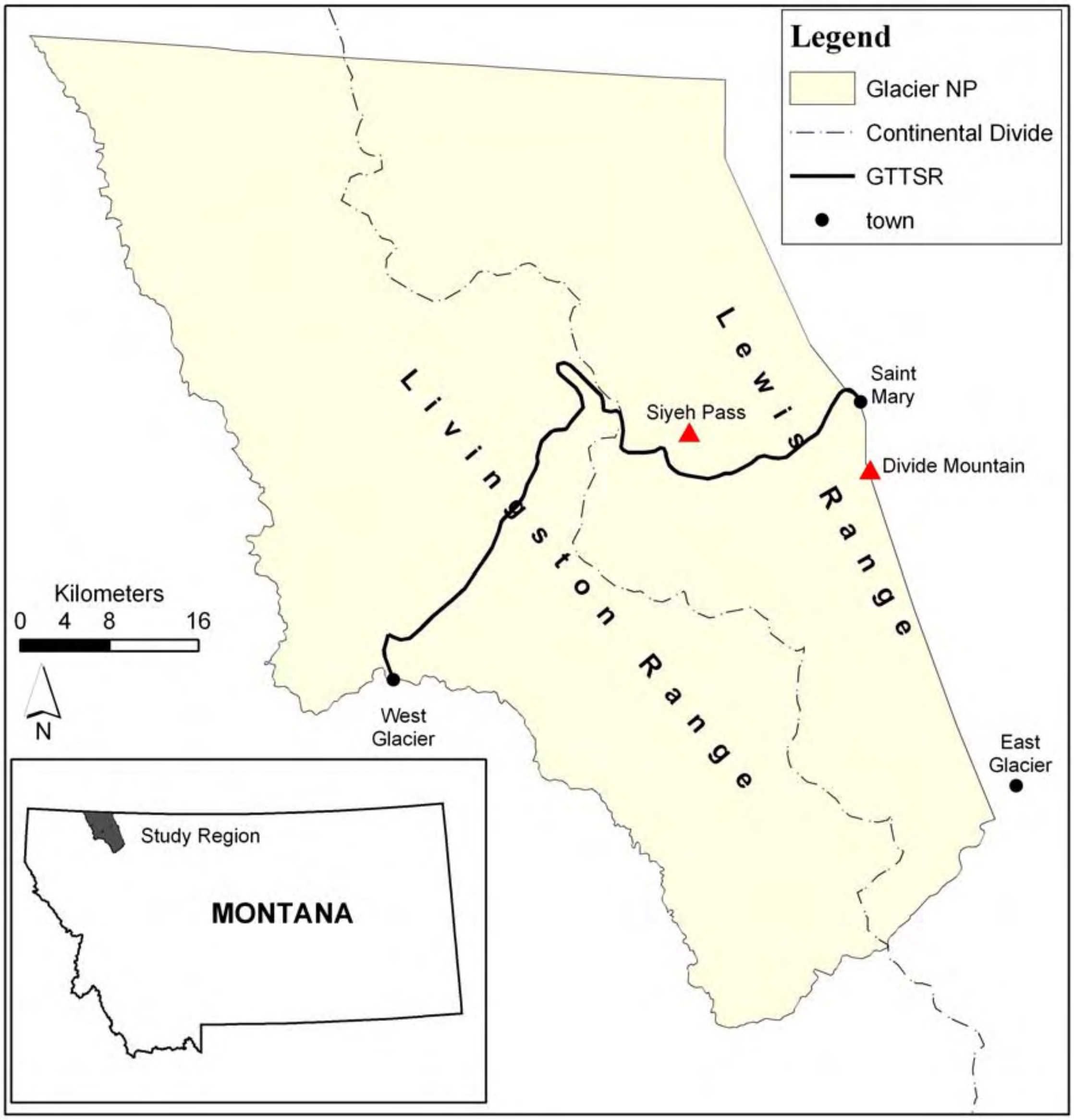


Figure 2. Study region map, GNP, MT.

Table 6. Characteristics of each site.
Colloquial names of each site in parenthesis in the location column.

Location	Site characteristics					Figure	Pan dimensions (cm)
	Aspect	Elevation (m)	Geology (Williams 1992)	Slope	Surficial geology		
Divide Mountain North	NNE (34°)	2144	Altyn limestone (Precambrian)	4°	Solifluction deposits	5	
Markers:							
Site A (Big Lip)						11	290 x 180
Site B (George)						12	163 x 131
Nails:							
Site C (Little Lip)						13	185 x 87
Site D (No Lip)						14	170 x 115
Divide Mountain South	South (189°)	2113	Altyn limestone (Precambrian)	1-3°	Solifluction deposits	5	
Markers:							
Site 1 (Hoofprint)						6	230 x 125
Site 2 (Deranged)						7	490 x 290
Site 3 (Porkchop)						8	320 x 195
Nails							
Site 4 (Rocky)						9	100 x 140
Site 5 (same as Site 2)						7	490 x 290
Site 6 (Lambchop)						10	250 x 150 (est.)
Siyeh Pass	East (100°)	2361	Helena Formation (middle Proterozoic)	4°	Solifluction deposits	15	
Markers and nails							
Site I (Rachel)						17	180 x 110
Site II (Gnomes)						18	120 x 90

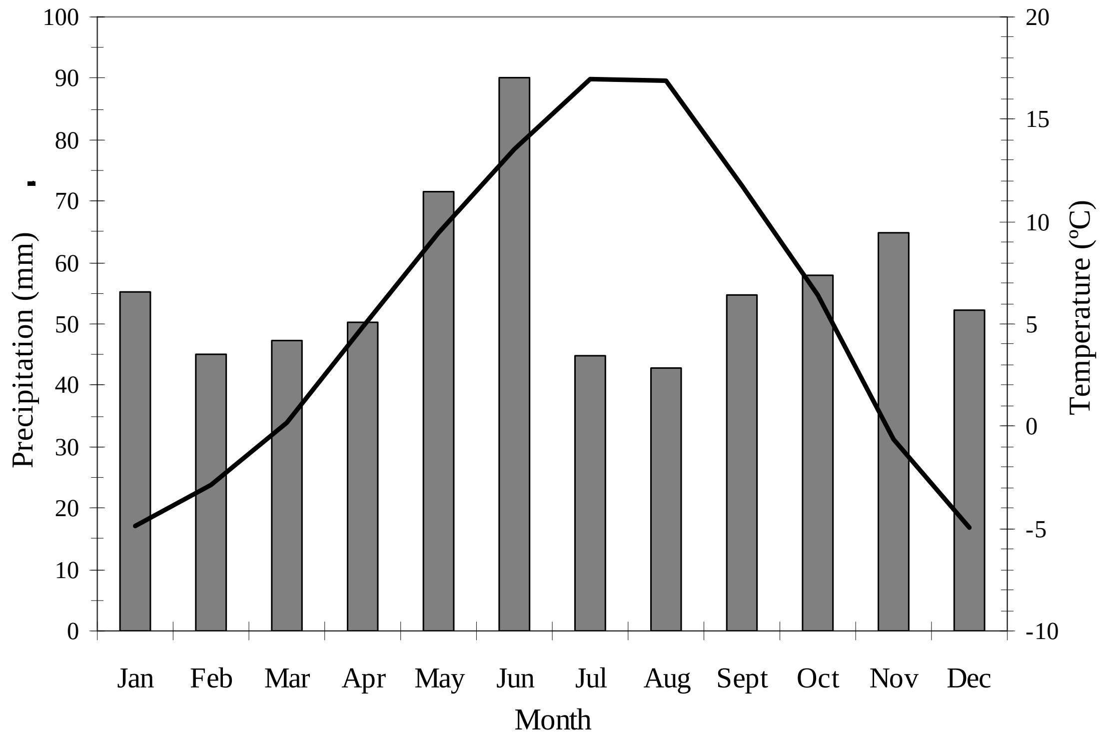


Figure 3. St. Mary, MT climograph, 1981-2005.

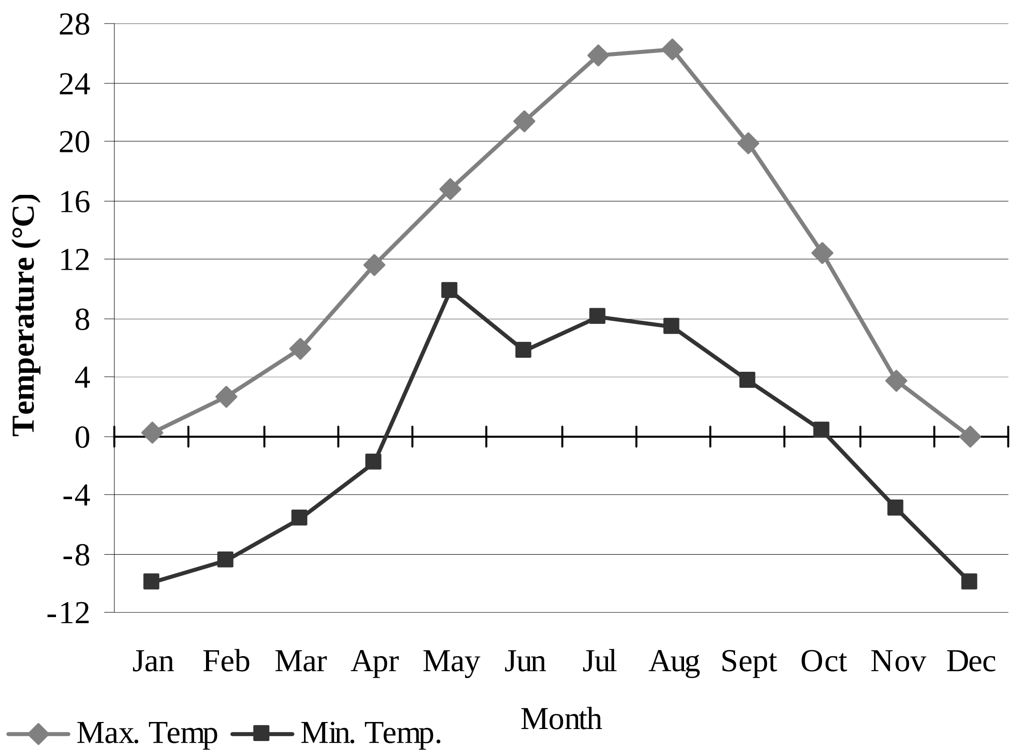


Figure 4. Minimum and maximum mean monthly temperatures, St. Mary, MT, 1981-2006.

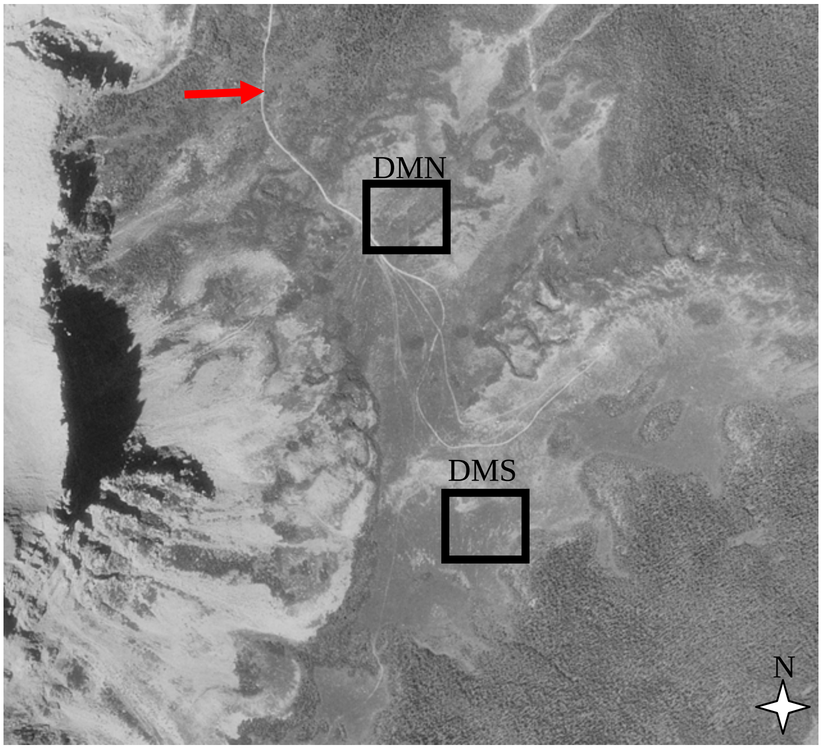


Figure 5. Divide Mountain aerial photograph, 1995.
For scale, red arrow is pointing to a gravel single lane access road.

Figure 6. Site 1 (Hoofprint), DMS.
Red arrow pointing to a U.S. Mint penny (19 cm) for scale.

Figure 7. Sites 2 and 5 (Deranged), DMS.
Person sitting on ground in upper right included for scale.

Figure 8. Site 3 (Porkchop), DMS.
For scale, circled rock is approximately 8 cm.

Figure 9. Site 4 (Rocky), DMS.
For scale, arrow is pointing to nail head.

Figure 10. Site 6 (Lambchop), DMS.
For scale, arrow is pointing to a nail head.

Figure 11. Site A (Big Lip), DMN.
For scale, arrow is pointing to a 49-mm lens cap.

Figure 12. Site B (George), DMN.
Person sitting on ground in upper right included for scale.

Figure 13. Site C (Little Big Lip), DMN.
For scale, arrow is pointing to a nail head.

Figure 14. Site D (No Lip), DMN.
For scale, arrow is pointing to a nail head.

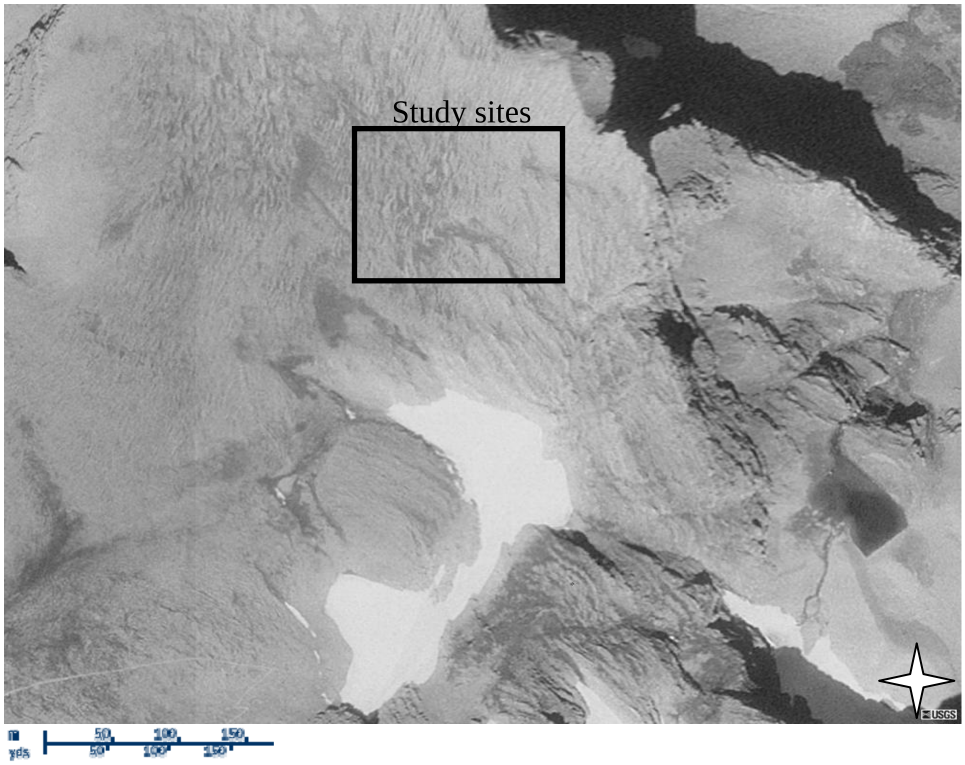


Figure 15. Siyeh Pass aerial photograph, 1995.

Figure 16. Siyeh Pass study area.

Figure 17. Site I (Rachel), SP.
Note daypack in center left of photo for scale.

Figure 18. Site II (Gnomes), SP.
Note daypack on upper left in photo from scale.

CHAPTER FOUR

DATA AND METHODS

Empirical data were obtained from the movements of markers, clasts, and nails located on the surface of pans. Methods for documenting movement patterns of markers and clasts at the study sites focused on repeat photography (Table 7). The steps taken in order to obtain the data were as follows: 1) markers were placed on the surface of 6 pans, 2) from initial site establishment photographs, distinctive clasts were chosen for observation, 3) the distance between the surface and nail heads, initially flush with the pan surface, was measured to calculate frost heaving, 4) the individual pans were re-photographed at seasonal intervals to obtain a static record of movement of clasts and markers, 5) site observations were completed, recording field measurements of markers, nail movement, site disturbances, and the micro environment, and 6) the results of surface movement, captured through field measurements and re-photography, were recorded.

The range of possible field methods was limited due to the sensitivity of the GNP region, which discouraged equipment easily observable by visitors, in addition to temporal limitations required to complete the project. Unobtrusive site methods provided another barrier to prevent visitors from likely discovering the study sites and disturbing them. In order to successfully complete the objective of investigating surface movements occurring in a patterned ground environment within eastern GNP, a framework was

Table 7. Methods used to answer research questions.

	Questions	Data and methods	Question answered when:
1	Is movement occurring at the study sites?	Repeat photography and field observations	Movement was/was not confirmed
2	What is the temporal and spatial movement of the individual surface clasts and markers?	Surface markers and clasts, repeat photography, and site observations	Temporal and spatial movement and changes in the pans recorded
3	Did the surface of the sites, as a whole, change in appearance?	Clasts, repeat photography, and site observations	Surficial appearances in the pans recorded
4	What is the amount of heave occurring at the study sites, temporally and spatially?	Nails and site observations	Amount the nail was heaved recorded

created, for answering the questions, including the methods used, and the point at which each question was completed.

Confirming surface movement (Question one)

Natural micro-scale changes of the appearance of the pan's surface at the study sites needed to be confirmed before further research was completed. To verify frequent and active changes at the study sites, photographs from multiple visits to the sites were used for comparison of the original site photographs. Further use of repeat photography for collecting data is described below.

Individual marker and clast movement (Question two)

To answer the question regarding timing and patterns of movement, two types of data, markers and surface clasts, were utilized, in conjunction with repeat photography and site observations.

Markers

Markers similar in size to medium-sized surface clasts within pans were used to observe how the surface changes over time. The markers were intended to replace the traditional method of painting stones or gravel along transects; however, the same results and methods used to collect data from painted transects or stones was achieved. Coins (U.S. one cent pieces, i.e. “pennies”) were placed on the surface to observe changes in their positions, both laterally and vertically, over time. Additionally, the incorporation of pennies with existing clasts and fine sediment was also examined. Pennies were chosen because of their ease of identification using repeat photography, their resistance to degrading or fracturing in the harsh climate, and because the method is not as invasive as other past research techniques, which include poring resin over a sorted polygon (Bunting and Jackson 1970), painting transects (Benedict 1992; Wilkerson 1995), and fixed horizontal bars across a surface (Kling 1997).

Clasts are defined, for the sake of this study, as pieces of rock at least 2 cm in length. Gravel is rock pieces smaller than 1 cm in length. Fine-grained sediment includes sand, silt, and clay.

At each study site, markers were placed in at least two individual pans (Appendix A). Fifteen markers were placed inside of each pan. Using more than fifteen markers was impractical given the size of some of the pans. At Divide Mountain, where possible, pennies were placed in the center of miniature sorted circles. The circles were generally less than 10 cm in diameter (Figure 6). At Siyeh Pass, miniature sorted circles were not present; therefore, markers were placed across the pans on top of gravel surfaces. Pennies at both Divide Mountain and Siyeh Pass were placed with the Lincoln Memorial facing up on a flat or near-flat surface. Additionally, pennies at each site were placed with the Lincoln Memorial oriented in the same direction. To follow the changes in lateral and vertical position, markers were compared to their previous positions when the site was last visited and photographed. Exact comparison was possible as the markers were identified based on surrounding surface clasts (Divide Mountain sites) or by numbers painted on the surface of the markers (Siyeh Pass sites).

Clasts

To further observe surface movement, 15 clasts laying on the surface of each pan were chosen and observed through repeat photography, to identify temporal and spatial patterns of vertical and lateral movement. Additionally, the interaction between clasts and surrounding gravel and fine sediment was recorded and compared to data collected from marker observations. Data from the clasts supplemented records collected from the markers placed on the surface. Using surface clasts increased the data set and helped alleviate overestimation of movement of the surface markers (Caine 1981).

Repeat photography

To observe not only the markers placed in the pans, but also surface clasts, repeat photography methods were used. This method ensured (1) collection of the data in a static form to compare previous and future locations of the markers and clasts, as well as the heaving of nails and (2) documentation of changes of the appearance of surfaces of the sites, in addition to changes occurring with and to the surface clasts and markers.

To adequately use repeat photography for data collection on clast and marker movement, high resolution imagery was necessary. The resolutions of satellite imagery and aerial photography were inadequate for this dissertation. Therefore, vertical or near-vertical images were acquired using a digital camera. Comparisons of images resulted in documented changes in the position of markers and clasts at different time scales. Photographs of each penny at each site visit were compiled into sets (Appendix C). Incomplete photo sets are listed in Appendix D. The appendix indicates dates of site visits when photographs were unavailable of a penny. The 2004 photographs at Sites 1, 2, and B were blurry due to camera malfunction, making data collection difficult or sometimes, not possible. Field notes from these sites greatly supplemented the information gathered from these photos. The field notes, written verbatim from the notebook, are in Appendix E. To accurately compare changes between two images, Jasc Paint Shop Pro software was used to rotate and crop images to match them to other images. The rotated images appear to have corners missing. Images were not manipulated in any other way.

Site observations

Site observations were completed to record changes in clast sorting, disturbances in and around each site, and the conditions of each site in conjunction with visits to re-photograph the sites (Appendix A). Ideally, site visits were to occur in every season as previous research by Grab (1997) noted that patterned ground can re-form annually within a 5-6 week time span. However, in some instances, travel to the study sites was not possible because of weather (March 2005), snow-blocked roads (March 2006), or heavy snowpack at the site (for Siyeh Pass only in September 2006). In another visit, data was only collected at one site at Divide Mountain (October 2005) because snow covered the other pans. Disturbances, either biotic or environmental, at or near each pan were recorded during each visit to ensure consideration of all factors related to changes in the sites, surface clasts, and markers.

Morphometric data from each site were collected during site visits. The slope at Siyeh Pass was calculated from a 1:24,000 topographic map. The slope at DMS and DMN was calculated in the field using a Brunton compass. Site aspect was determined from topographic maps. Pan size was calculated by measuring the x and y axis of each pan with measuring tape.

Site changes (Question three)

The sites were originally chosen based partially on their appearance (in addition to their location and size). For instance, Site 1 (Hoofprint, DMS) contained well-developed miniature sorted circles in 2003 when sites were first chosen (Figure 6). The site was chosen because of its uniqueness and to see the changes that occurred on the surface of the pans over time. Therefore, the third question was to observe changes in the overall surface appearance of the pans to see how they are evolving on a seasonal and annual basis. To accomplish this, I compared photographs taken throughout the study of each site to determine what, if any, changes occurred. The same techniques described under the "Question Two" subheading were used and the data collected for both these questions overlap. In particular, to answer question three, repeat photography of the sites was used. Additionally, changes in the positions of markers placed into particular circles were traced.

Surface heaving (Question four)

Measurement of surface heaving at the study sites was needed to confirm that upward movement was occurring. If no heaving could be confirmed, i.e. no upward expansion of the surface during the year, then the idea of surface movement being associated or a result of frost-related processes would be difficult to establish. To prove heaving is occurring and to measure the amount of heaving over a year, 10d galvanized nails, 7.7 cm (3 inches) long with an 8 mm nail head, were placed randomly into the ground in the pans at DMN, DMS, and SP (Appendix A). Ten to 20 nails were placed in each pan (Appendix A), depending on the size of the pan, and pushed completely into the surface until the nail head was level with surrounding clasts or fine-grained sediment. Nails were placed semi-randomly because of the coarseness of the pans and because obstacles (i.e. large rocks and gravel) in the pans prevented use of a grid or stratified pattern. Each nail was measured, to the millimeter, as to the amount it heaved. Wooden dowels were not used because of questions concerning expansion of the dowels from water saturation, subsequent freezing, and breakage or decaying of the dowels from the harsh climate.

Missing data

One-hundred and five pennies and 90 nails were placed in seven pans between 2003 and 2005; however, one pan, Site II (Gnomes, SP) was not visited in 2006 (Appendix A). Therefore, the final data set was comprised of 90 pennies, 90 clasts (15 clasts each from the remaining 6 pans), and 80 nails, whose movements were recorded over a 2 month to 39 month period (Appendix A). Appendix D lists dates when photographs from each site were not collected or available. No photographs were available of three pennies (numbers 8, 9, and 10) at Site 2. Photographs are unavailable for Site A (Big Lip) for 2005; however, Appendix J contains data on pennies overturning in August 2005. These data were able to be determined without the use of photographs because, on the Divide Mountain pennies, a small blue mark was placed on the side of the penny facing up. Therefore, in the 2006 photographs, if a penny was seen with a blue mark, then that was the face of the penny in 2005 (Figure 19).

Figure 19. Penny 6, Site A, DMN.
Photo illustrates how pennies were marked with a blue dot (arrow) in 2005.

Analysis

To synthesize the data collected from markers and clasts, a classification system was created to record the position movement of each penny and clast. This system was in addition to the penny relocation, which is defined as whether a penny or clast was located during each site visit. The clast and marker data were recorded in Excel spreadsheets and are summarized in the Results chapter. The definitions of each variable for markers and clasts are discussed below.

Site changes

Changes in the surface of the pans were determined using sets of photographs taken during each site visit.

Markers

To observe the overall directions of marker movement, diagrams of each pan were created with the drawing tools available in the Microsoft Office Suite. The diagrams are based on the initial photographs taken of each site after the markers were placed. The location of each penny was marked used colored dots. The current or last known location of the pennies is noted using different colored circles. The lateral movements are shown using arrows. Vertical tilt and burial are indicated by distorting the shape of the circles representing the pennies.

Changes in a penny's position were quantified using four variables observable through repeat photography: (1) amount of penny burial, (2) overturning, (3) the penny's vertical tilt, and (4) lateral movement (cf. Appendix G). Numerical variables were used to quantify a penny's movement. A null value of "0" was used with each of the variables to indicate a position representative to the penny as it was initially placed.

By classifying a penny as buried, the penny was partially covered by sediment or clasts. Four levels of burial were: 0 = no burial; 1 = 0 – 33 %; 2 = 33 – 66%; and 3 = 66% and above. The levels of burial were applied to a penny as if the penny's diameter (19 mm) was equally-divided into thirds (instead of equal area). Equal-length intervals were chosen as it was deemed better suited when using photographs. For example, Table 8 is the data on penny 1 at Site 1 (Hoofprint, DMS). The first row is burial. When the penny was observed in July 2004, it was over one-third buried (as indicated by the "2" in the first column). In August 2005 and thereafter, it was over two-thirds buried (as indicated by the "3").

The variable "lateral movement" was utilized to observe the changes in the surface position of a penny between two site visits. A low threshold was used to rate whether any lateral movement had occurred between site visits, including rotational and surface movement. Originally, the amount of lateral movement measured to the millimeter was planned; however, observations showed that the pennies rarely moved in measurable units across the surface, but rather moved within a small area and included rotational movement. Therefore, any observed movement was assigned a "1". For example, row 2 in Table 8 contains the results of lateral movement of penny 1 at Site 1 (Hoofprint, DMS). When the penny was observed in July 2004, it had moved from its original position (as indicated by the "1" in the first column). Thereafter, it did not move and a "0" was noted for lateral movement each visit after July 2004.

"Overturning" referred to a penny flipping between the Lincoln Memorial and Lincoln Profile sides. Pennies were initially placed with the Lincoln Memorial facing up, and therefore a penny was assigned "0" if that side of the penny was facing up during subsequent site visits. Pennies with Lincoln's Profile facing up were assigned a "1". The term "n/a" was used when the penny was vertical and was not preferentially showing neither Lincoln's Profile (i.e. heads) nor the Lincoln Memorial (i.e. tails). In some instances, the penny was tilted vertically but leaning against a rock and the profile of the penny could easily be determined and was so noted. For example, row 3 in Table 8 contains the results of penny 1 overturning at Site 1 (Hoofprint, DMS). When the penny was observed in July 2004, it had overturned and Lincoln's Profile was facing up (as noted by the "1" in the first column). Thereafter, it remained with Lincoln's Profile facing up and a "1" was marked for overturning for each visit after July 2004.

The penny's vertical tilt was quantified after observing and photographing pennies placed in soil with a 180° protractor placed in the background. The three levels of vertical tilt that were identifiable in photographs were (in addition to 0): 1 = 5 – 30°; 2 = 30 – 60°; and 3 = 60 – 90°. Any angle below 5° was considered to be minimal to no vertical tilt. For example, row 4 in Table 8 contains the results of penny 1's vertical tilt at Site 1 (Hoofprint, DMS). When the penny was observed in July 2004, it was tilting at over a 30° angle (as noted by the "2" in the first column). The penny remained at the

Table 8. Example of data collected from pennies at Site 1, DMS.

ID	Variable	7-2004	8-2005	7-2006	9-2006
1	Burial	2	3	3	3
	Lateral (cm)	1	0	0	0
	Overturn	1	1	1	1
	Vertical	2	2	2	2

same vertical tilt through September 2006; and for every site visit after July 2004, a “2” was noted.

Clasts

Clast movement was not adequately explained using the above four variables. Therefore, the four variables used to classify movement of clasts were: (1) overturning; (2) burial; (3) rotation; and (4) lateral movement. Vertical tilting, used to describe penny movement, was rarely observed with clasts, and if vertical tilting did occur, it was not quantifiable; therefore, the variable was not used. For overturning, if clasts changed positions to a new exposed side, a “1” was recorded. Clasts were assigned a “0” if the surface of the clasts was the same as when the site was last visited (cf. Table 9).

The same categories of burial that were used with pennies were applied to the clasts with the addition of negative numbers (i.e. -1, -2, and -3). Negative numbers were included because unlike pennies, which were placed on the surfaces of the pans, clasts were sometimes chosen that were already partially buried. Rather than only choosing clasts that were not buried, minus signs were placed before the number to represent how buried the clasts was on the first visit. For instance, if a clast was half buried in 2003 and was laying on the surface when the site was visited in 2004, a “-2” was assigned for 2004 to indicate the clast had been buried when the study began but was no longer buried (cf. Table 9).

Clast rotation was also included as a variable. The change in the azimuthal direction (i.e. rotation) of the clasts was determined by drawing a line, in Microsoft Powerpoint, along the long axis of the clast on the first-time photograph of the clast. For instance, for Site 1 at DMS, photographs from 2003 were used to draw the line on each clast. The line was then copied and pasted onto the next sequential photograph (for Site 1, the next set of photographs was from 2004). If the clast had not moved between site visits, the line would follow the long axis of the clast. If the clast had rotated, the line was rotated until the line once again bisected the long axis of the clast. The range of possible amounts of rotation was from 0 to 180°. The rotation was negative if the line was rotated to the left and positive if the line was rotated to the right. Two rotation amounts are given for each clast: first, in parenthesis, the actual amount of rotation needed to realign the line with the clast; and second, the total change in azimuth (cf. Table 9). The degree of rotation does not assume 0° is north but rather the original long-axis orientation of the clast. Using clast 1 at Site 1, DMS, as an example: in 2004, the line drawn on the 2003 photograph was off-centered from the long-axis by 15°. The line was rotated 15° to bisect the clast. The line was rotated a further another 35° to match the long-axis orientation of the clast in 2005. Therefore, the clast rotated 50° between the 2003 and 2005 photograph. In July 2006, the clast had rotated an additional 15° and by September 2006, another 5°.

The categories of classification of lateral movement were changed to reflect numerical measurements of the movement of clasts across the surface. To measure the distance a clast moved over time, a set of photographs containing the selected clasts and a penny from consecutive site visits were assembled. In the set, the new photo was calibrated to the older image, enlarging one photo to make the pennies in both images the same size. Then in the older image, using the drawing tools in Microsoft Powerpoint, a line was drawn across the penny to create a line 19 mm long (the diameter of a penny). The original position of the clast was located on the new image. A line was then drawn from the original position of the clast to the new location, using the most direct route. The number of 19 mm-long lines needed to go between the two locations gave the distance traveled by the clast. For instance, if 2 ½ lines were needed to cover the distance between the previous and new position, then the approximate distance traveled was 47.5 mm or 4.75 cm. This amount is assumed to be approximate, and could be either an overestimate or underestimate of the actual distance traveled between visits. However, the method provides a rudimentary technique for comparing distances traveled between the clasts, and differences between clast movements between the sites. This method was impractical for penny movement (cf. Table 9).

Table 9. Example of clast data collected at Site I, DMS.

ID	Variable	Jul-04	Aug-05	Jul-06	Sep-06
1	Burial	-2	0	0	0
	Rotation (°)	(-15) 345	(-35) 310	(-15) 295	(-5) 290
	Overturn	0	0	0	0
	Lateral (cm)	2.85	2.85	0	0

Nails

To observe the overall heaving of nails at Siyeh Pass, a diagram of the distribution of nails at Site I was created with the drawing tools available in the Microsoft Office Suite. The diagram was based on the initial photographs taken in 2005 of Site I after the nails were placed. In the diagram, each nail was color-coded by the amount it was heaved. After the heaving data were collected in 2006, the circles, representing the location of the nails in the pan, were then classified using natural breaks to divide the heaving amounts into three categories (minimum, medium, and maximum). Heaving amounts and data collected at DMN and DMS were not adequate for creating diagram of the nails that were heaved at those sites.

Statistics

Descriptive statistics were used to report the rates and patterns of movement of markers and clasts, in addition to the rate of frost heaving. Inferential statistical testing was originally planned for this dissertation. Non-parametric statistical tests were to be used because the data violated the assumptions necessary for parametric testing, especially the assumption that the study sites were randomly chosen. Three tests were planned. First, the Mann-Whitney U Test was to be used on the nail heaving data from DMS and DMN to determine if the amount of heave at the two sites were from the same population. However, the data collected from DMS and DMN were incomplete, thus not allowing for test completion. The second planned test was the Kruskall-Wallis one-way analysis of variance. This test compares the results from different samples to determine if they were from the same population. Data collected on the nail rate of heaving could not be used because only 1 set of quantitative heaving rates were available (Site I, Rachel, SP). Penny data were not useable because it could not be ranked to a satisfactory level, a requirement for the Kruskall-Wallis test. The third test, Kendall's Coefficient of Concordance, was to test two ordinal levels of data (burial and vertical tilt) between the sites to see if the results obtained were in agreement. This test was discarded because three variables were needed for this test.

CHAPTER FIVE

RESULTS

Movement patterns of surface clasts and markers in an alpine tundra environment were observed over several seasons. The results are divided into the proceeding five sections for clarity. The first section reports the findings of verifying surface movement within the pans. This surface movement confirmation is done by reporting on two changes that occurred to the pennies placed on the surface: overturning and relocation of the pennies. The second section contains the findings of temporal changes in the surfaces of the pans, specifically at Sites 1 and 2. The third, fourth, and fifth sections contain the results of the movement of pennies, markers, and nails. In each of these sections, the findings from each pan are presented separately, with the exception of the section on nails. This section was divided into the two main study sites, Divide Mountain and Siyeh Pass.

Confirmation of surface movement

Active movement on the surface of the study sites was confirmed through the use of markers and observed using repeat photography recording changes in the position of pennies during site visits. These changes include overturning, unsuccessful penny relocation, and penny entrainment with gravel and clasts, all of which confirm activity related to frost processes and refute movement caused by animals and/or water.

Active movement was confirmed first in 2004, one year after initial site establishment of Sites 1 (Hoofprint), 2 (Deranged), and B (George), by penny overturning (cf. Figure 20). One year after placement, five of the six study sites had at least one penny that overturned at least once (Table 10). The overturning results are conservative, because they do not take into account false readings; i.e. where a penny may have overturned at least twice, thereby continuing to show the Lincoln Memorial. Additionally, because pennies were not continuously observed, they may have overturned many times between site visits. Twenty-five of the ninety pennies at the 6 sites were laying on the surface with Lincoln's Profile facing up.

Table 10. Number of overturned pennies observed one year after placement.

Site	Number of pennies overturned (Lincoln's Profile facing up)
Divide Mountain South	
1 (Hoofprint)	2 (11 total found), plus 7 either buried or tipped
2 (Deranged)	5 (12 total found)
3 (Porkchop)	7 (15 total found), face of 1 penny could not be determined
Divide Mountain North	
A (Big Lip)	0 (7 total found), plus 2 buried and tipped
B (George)	5 (15 total found), plus 1 resting at a 90° angle
Siyeh Pass	
I (Rachel)	6 (14 total found)

Figure 20. Example of overturning, Penny 13, Site I, SP.
Left (hereafter L) photo from 2005 and right (hereafter R) photo from 2006.

Only one site (Site A, Big Lip, DMN), did not have any pennies showing Lincoln's Profile. Also, the fewest amount of pennies were located at this site one year after placement. Almost half of the pennies at Site 3 at DMS had overturned at least once since they were placed, the highest number of overturned pennies.

In general, the total number of pennies located each year decreased, from 74% in year one to 64% in three year after placement as one year after placement, a mean number of 12 pennies were found at each site. This number decreased to 9 by year three; although the number of sites with three years of data also decreased. Appendix B lists each individual penny, by site, and notes whether the penny was located during each visit made to the sites.

The success rate of relocating pennies at each site ranged from between 47% and 100% one year after placement (Table 11). For instance, at Site 2 (DMS), penny 6 was placed in 2003 (Figure 21). In 2004, the penny was not visible and the penny has not been visible or located during any of the subsequent site visits. At Site A, at DMN, the fewest number of pennies were found (7), whereas at two sites (Site 3 at DMS and Site B at DMN), all 15 pennies were relocated. During the second year site visit following placement, the lowest rate of relocating pennies increased from 47% (at Site A) in year one to 53 % (at Site 2) in year two. Of the four sites with 2-year data, two sites (Sites 2 and 3) decreased in the number of pennies located from the previous year. Site A had the most extreme change between the two years, with all pennies found in year two whereas only seven were found in year one. Three-year data are available for three sites. Success rates of locating pennies decreased at two sites, losing 3 pennies at Site 1 and 1 penny at Site B.

Table 11. Success of relocating pennies following placement.

Site	Number of markers relocated (%)		
	1 year after placement	2 years after placement	3 years after placement
Divide Mountain South			
1 (Hoofprint)	10 (67)	10 (67)	7 (47)
2 (Deranged)	9 (60)	8 (53)	9 (60)
3 (Porkchop)	15 (100)	12 (80)	
Divide Mountain North			
A (Big Lip)	7 (47)	15 (100)	
B (George)	15 (100)	n/a	14 (93)
Siyeh Pass			
I (Rachel)	14 (93)		
Number of markers in each year's sample	90	60	45
Total markers relocated	70 (78)	45 (75)	29 (64)
Total number of markers not found	20	15	16
Mean and median number of markers relocated	12 (13)	11 (11)	9 (9)

The table is arranged for the comparison in the number of pennies located at each site at equal time intervals (i.e. success of relocating pennies in year one).

Figure 21. Penny 6, Site 2, DMS.
2003 (L) and 2004 (R, penny not found).

Figure 22. Penny 3, Site 1, DMS.
August 2005 (L) and July 2006 (R).
Before July 2006, penny was not located since 2003.

Site changes

The surficial appearance of the six study sites changed over time, but two sites (Sites 1 and 2 at DMS) had especially distinctive changes illustrative of the evolution of the sites over time. Before the changes at those sites are discussed, the changes observed at the other four sites are evaluated.

When the sites were established at Divide Mountain, miniature sorted circles (i.e. circles less than 20 cm) were present at 3 (Sites 1, 2, and 3 at DMS) of the 6 study sites.

Sites 1 and 2 are discussed individually. Site 3 (Porkchop, DMS) had poorly developed circles in 2004 (the year the site was established) and 2005 (Figure 23, red arrow points to a sorted circle with blue arrow indicating a penny for scale). In July 2006, fewer than 5 miniature “frost boils” (green arrow in Figure 23) were seen at Site 3. Sorted circles were not present in 2006.

Sites A and B (Big Lip and George, DMN) contained more fine-grained sediment than the sites at DMS and SP and each DMN site was considered to be a single nonsorted polygon. The primary change in the surface appearances of sites A and B was the fluctuating amount of rock and clasts exposed from the sediment (Figure 24). In the September 2005 photograph (Figure 24, L), clasts were visible and clean with moist fine-grained sediment deposited around the clasts. By July 2006 (Figure 24, R), sediment had covered some of the clasts.

At Siyeh Pass, Site I was dominated by clasts with little fine-grained sediment (Figure 25). In 2005, when the pennies were first placed at the site, the site had the appearance of a nonsorted polygon (Figure 25, L). However, a few miniature sorted circles were located in the site (blue arrow) but the centers were ill-defined. For example, penny 8 (red arrow) was placed in the center of one sorted circle. When the site was re-visited in 2006, the sorted circle which held penny 8 has disappeared, with only one of the three sorted circles identified in the 2005 photo still present (center blue arrow) (Figure 25, R).

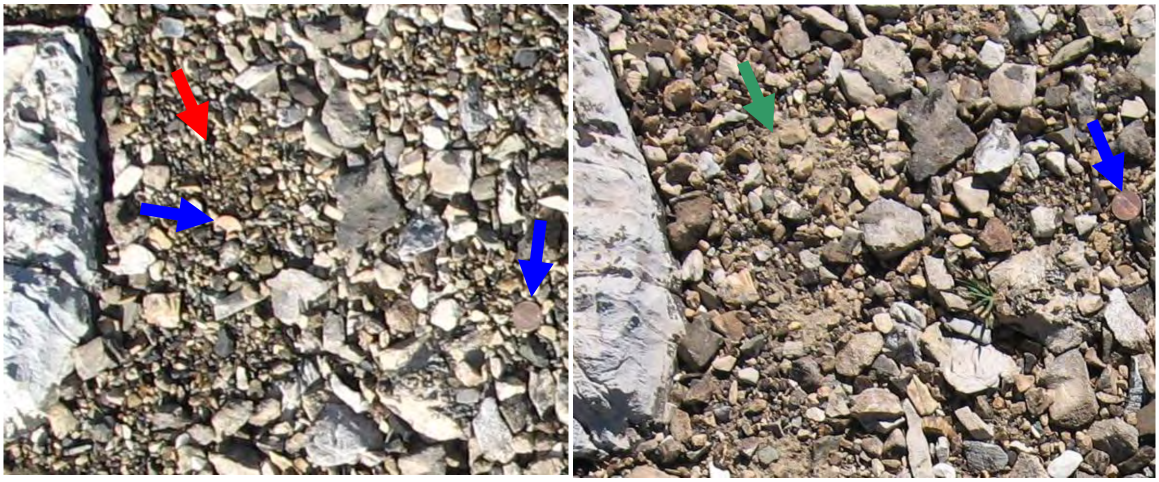


Figure 23. Site 3, DMS, May 2005 (L) and July 2006 (R).
Pennies (blue arrows); frost boils (green arrow, R); poorly sorted circles (red arrow).

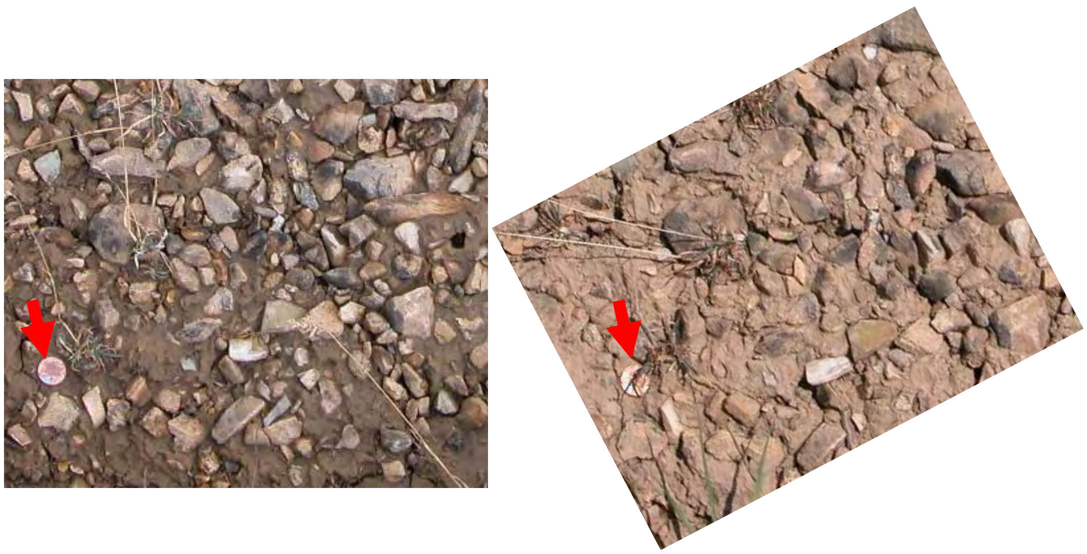


Figure 24. Site A, DMN, September 2005 (L) and July 2006 (R).
Penny 1 (arrows) indicated for scale and orientation.

Figure 25. Site I, SP, 2005 (L) and 2006 (R).
Penny 8 (red arrow) for scale (not located in 2006).
Blue arrows indicate poorly sorted circles.

Site 1 (Hoofprint), DMS. Established 2003

Site 1, DMS, was the first site established in the study. The pan was originally selected because of the presence of well-defined miniature sorted circles present in the pan in 2003 (Figure 26). Photographs of a section of the pan (which contain half of the pennies) document how the surface and pennies placed on the surface changed over four years. Overall, the site changed from a pan with distinct sorted circles to a nonsorted patterned ground environment and then, during the last site visit, new poorly defined sorted circles.

In 2003, pennies were placed in the centers of well-developed sorted circles. Six of these sorted circles and part of a seventh are shown in Figure 26, immediately following penny placement. One of the sorted circles seen in Figure 26 is indicated with a red circle. The sorted circles contain fine-grained sediment in the centers. Very little large gravel is present, but several large clasts are visible toward the right of the photo. Seven of the fifteen pennies placed in this pan are visible in the photograph, illustrating their initial location.

By the time the site was re-visited one year later, in 2004, the sorted circles had begun to collapse, with fine sediment mixing with gravel and clasts (Figure 27). A large amount of small gravel is now visible within the areas previously occupied by the sorted circles. A gutter of clasts is still evident along the lower former boundaries of the miniature sorted circles (red arrow on Figure 27). The red circle in the lower center of the photograph highlights the condition of the same area highlighted by the red circle in Figure 26. In 2004, the former sorted circle now has a “boil”-like appearance with a raised center and the penny entrained in fine sediment on the edge of the boil. Three pennies in this area of the pan (pennies 3, 4, and 6) are no longer visible.

In 2005, the same area noted by the red circle was no longer elevated, and the penny that was half “captured” by fine sediment was lying flat on the surface, with Lincoln’s Profile facing up (Figure 28). The gutter of clasts was still present, although the gutter was now wider. Some clasts in the gutter region were resting at different positions and angles than when the area was photographed in 2004. The areas where the sorted circles existed in 2003 present a distinctly nonsorted patterned ground in 2005. During the intervening year, an ungulate traveled through the edge of the pan, leaving a hoof print in the lower left portion of the photograph (one of three visible during the site visit, green arrow in Figure 28). Because of the hoof print, penny 4, not seen in 2004, was now visible (red arrow). Five of the seven pennies originally placed in this area were visible.

By the July 2006 site visit, sorted circles had begun to form with centers of fine sediment (Figure 29). The red circle in Figure 29 notes the location of a sorted circle present in 2003. Whereas in 2005 the red circle area contained a mix of gravel and fine sediment, by the time of the 2006 site visit, the area was completely transformed into an area of hardened fine sediment. Additionally, penny 5, clearly visible in 2005, is no longer there nor anywhere in the vicinity in 2006. Of the original seven pennies placed in this concentrated area of Site 1, only 3 could be identified, one of which (penny 6) was almost completely buried (Figure 30) and was not found in 2004 and 2005.

At the time of the September 2006 visit, the area of hardened fine sediment (marked by the red circle on the photograph) was still present but no other areas where sorted circles may be developing were seen (Figure 31). The line of clasts and gravel that initially was the gutter to several sorted circles in 2003 continues to be well-developed and wider. Penny 12 is shown resting at a 90° angle in the gutter. The pan’s surface above the clasts gutter is lightly covered with gravel underlain with fine sediment. Penny 7 is the only other penny in this area still present 3 years after placement.

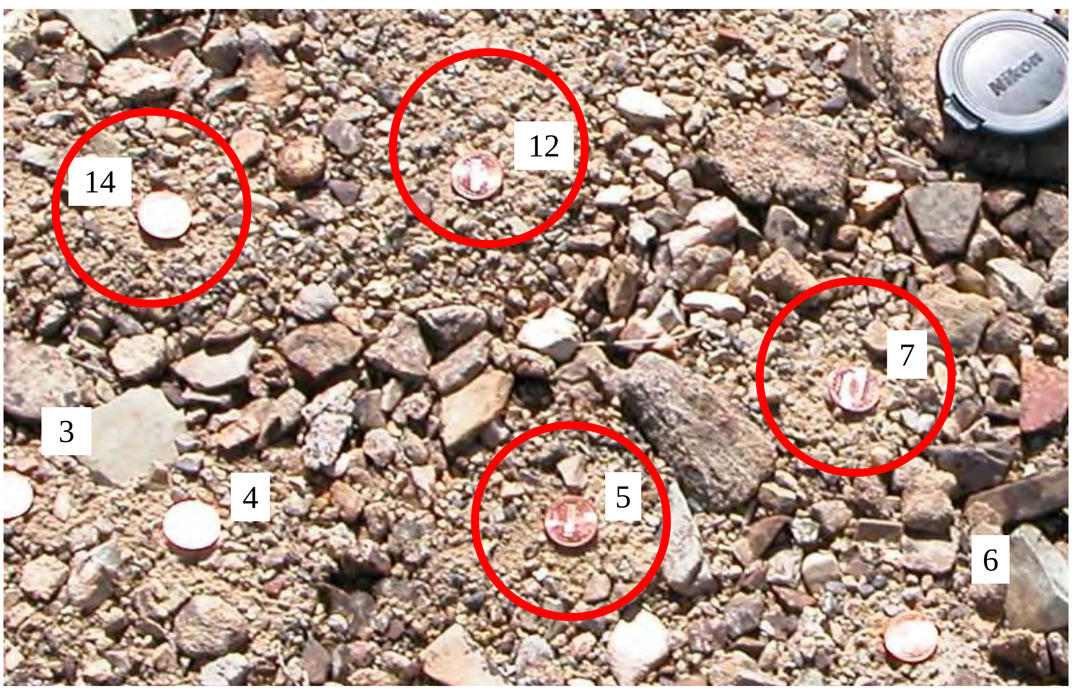


Figure 26. Site 1, DMS, 2003.
Several miniature sorted circles with pennies in center are denoted by circles.

Figure 27. Site 1, DMS, 2004.
Note the breakdown of the sorted circles and the loss of pennies 3, 6, and 4.

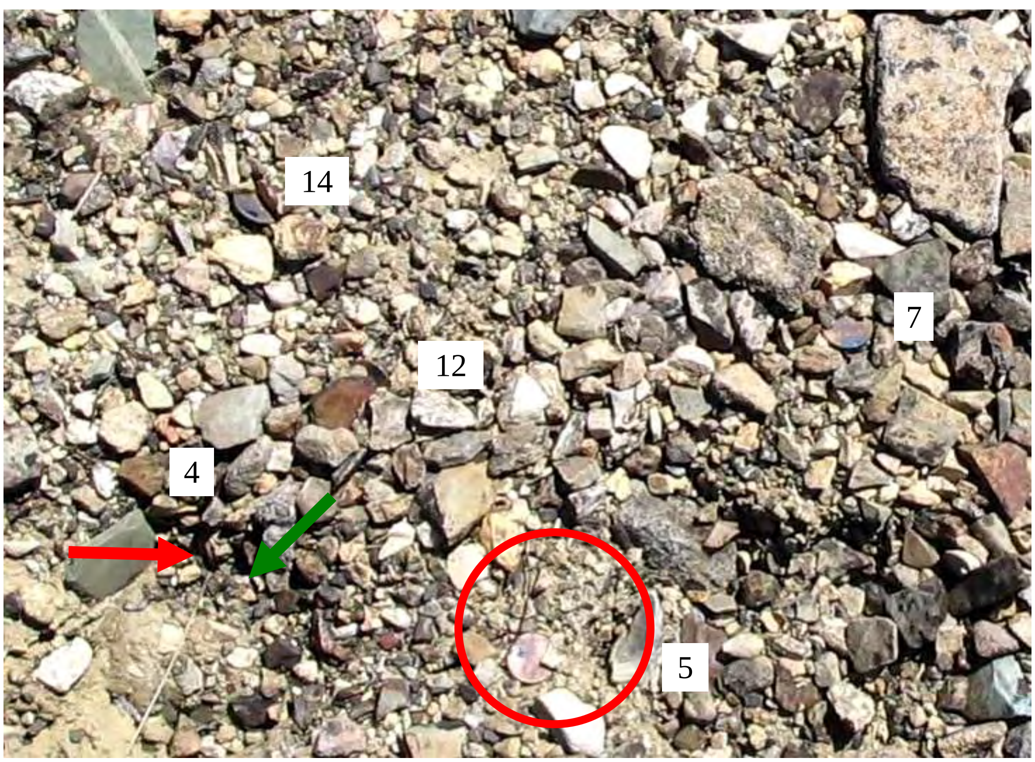


Figure 28. Site 1, DMS, 2005.
Penny 4 (red arrow) visible at the edge of a hoofprint (green arrow).

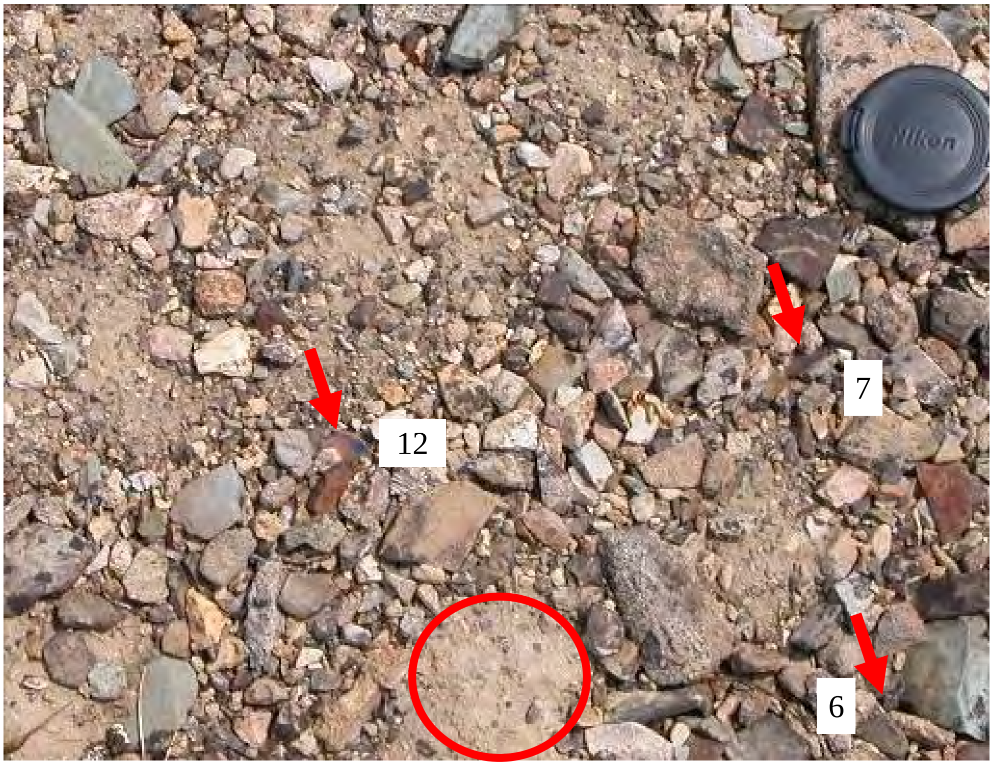


Figure 29. Site 1, DMS, July 2006.
Frost boil-like circles forming (e.g. circle). Three pennies were found (arrows).

Figure 30. Penny 6 (arrow), Site 1, DMS, July 2006.

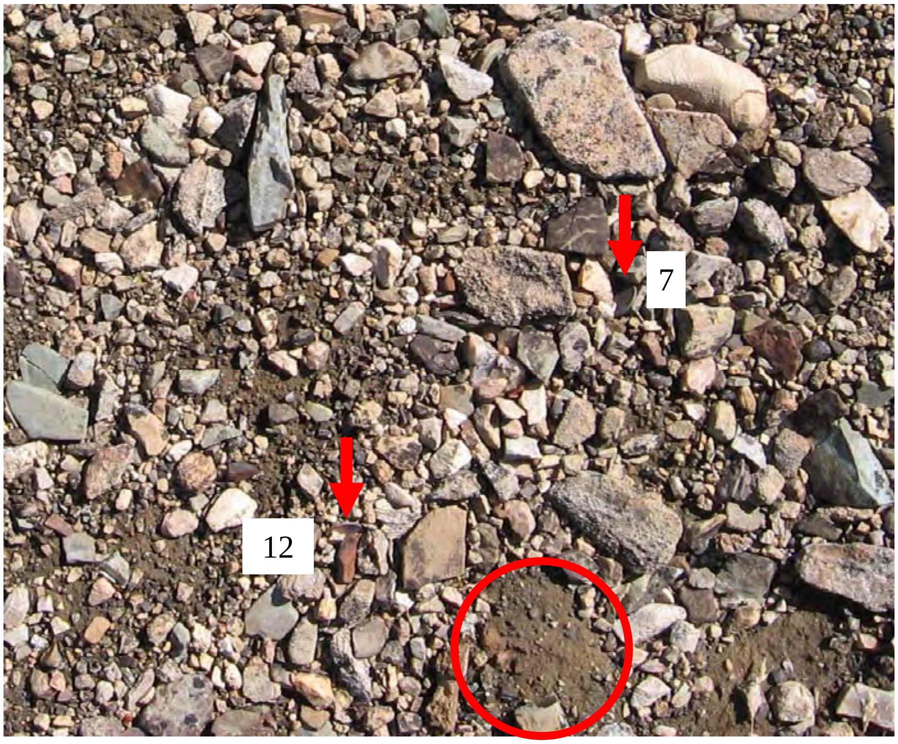


Figure 31. Site 1, DMS, September 2006.
Frost-boil like circles continue to form (red circle). Two pennies are still visible.

Site 2 (Deranged), DMS. Established 2003

Site 2 was established in 2003. Site-change photographic documentation is only available for a small portion of the pan (Figure 32) containing 5 pennies. This portion of the pan contained miniature sorted circles when the site was established in 2003. Five pennies were placed in the most developed circles. The sorted circles had small fine-grained sediment centers, smaller than those seen at Site 1 (see Figure 26). At Site 2, pennies cover most of the circle centers; whereas at Site 1, the centers were larger than the pennies.

When Site 2 was visited in 2004, half of the sorted circles were no longer visible (Figure 33) with the other half partially broken down. The remaining sorted circles were located along the edge of the pan and contained the original location of pennies 1 and 2.

These areas have dense concentrations of hardened fine sediment. A crack in the sediment is evident near the original location of penny 1. The area where penny 5 was originally placed is now completed unsorted with a mixture of gravel, clasts, and fines. Penny 3's original location also lost any semblance of a sorted circle. Penny 3 now rests at a 90° angle between pieces of gravel. Unlike Site 1, where the photograph from 2004 (Figure 27) showed areas of frost boil-like features where sorted circles were the previous year, the surface of Site 2 took the appearance of nonsorted patterned ground one year after sorted circles were observed in the pan.

In 2005, the hardened sediment, visible in 2004 along the lower edge of the pan, became less obvious (Figure 34). Gravel and small clasts dominated the area with little surface exposure of a gravel and fine sediment mixture. Penny 3 was not found in 2005; however, the other pennies are laying almost horizontally on the surface with little to no clasts or gravel on top of the pennies.

In July 2006, new small centers of fine sediment had begun to form near penny 5, possibly in the early stages of forming new sorted circles (Figure 35). The four pennies still visible have become partially covered by gravel (pennies 1, 4, and 5) or partially buried in sediment (penny 2). The four pennies were still visible during the September 2006 visit (Figure 36). Penny 4 became covered with small gravel during the 2 months between visits whereas penny 2 became more exposed (Figure 36). Penny 1 is now covered by twigs (rather than clasts like the other pennies), obscuring it from easily being viewed. During the 3 year observation period, the edge of pan remained distinct with no establishment of vegetation.

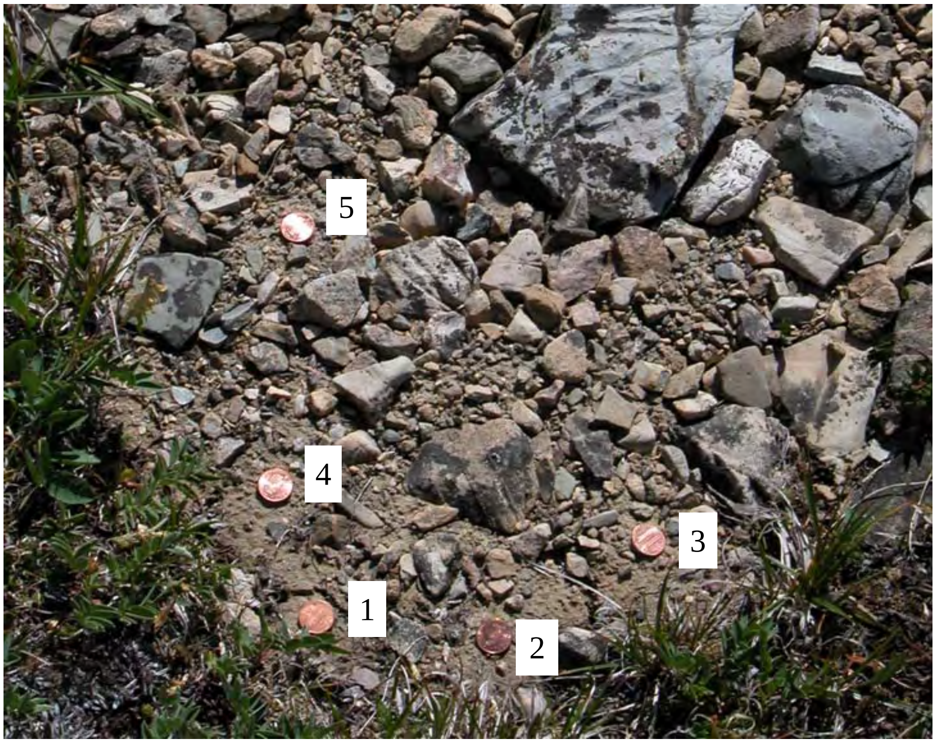


Figure 32. Site 2, DMS, 2003.
Pennies were placed onto the center of sorted features.

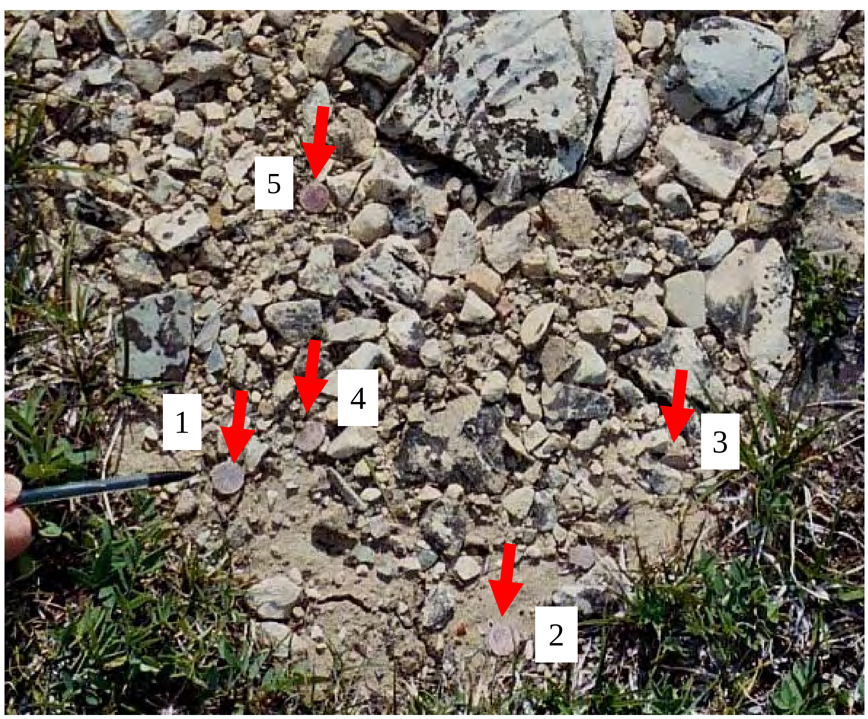


Figure 33. Site 2, DMS, 2004 with 5 pennies (arrows).

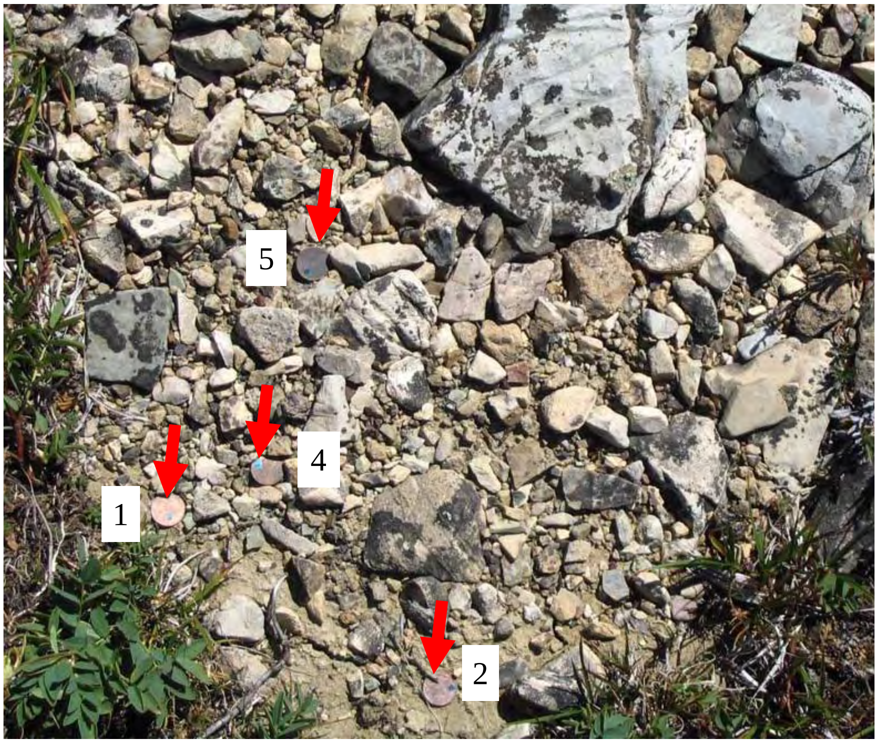


Figure 34. Site 2, DMS, 2005.
Sorted features observed 2 years previously are now nonexistent.
Four pennies are still visible (arrows).

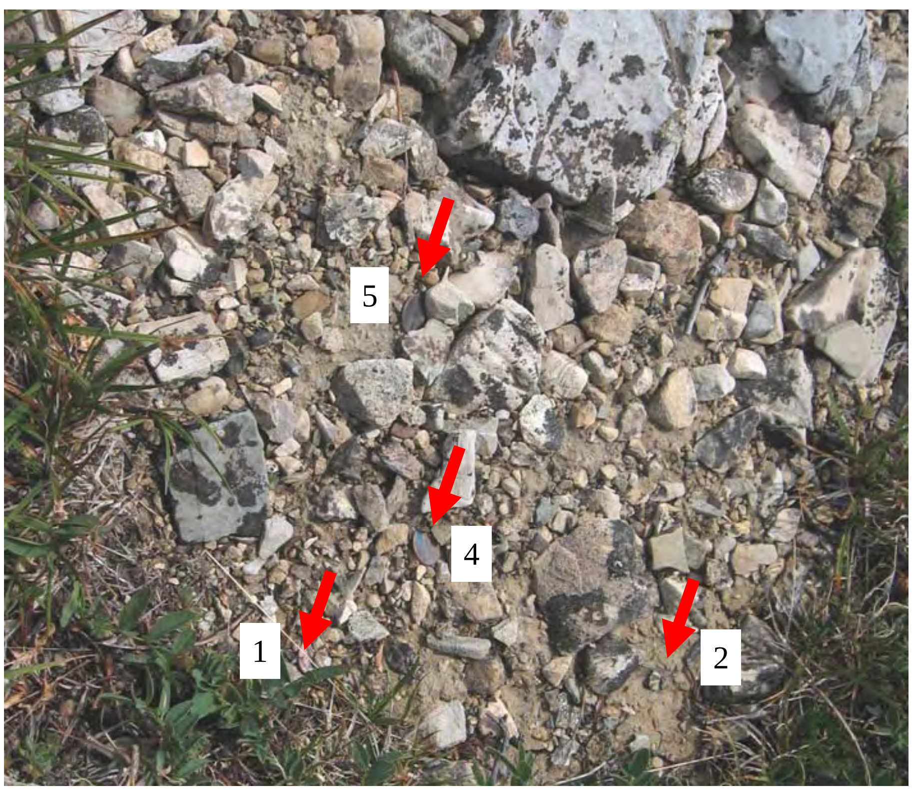


Figure 35. Site 2, DMS, July 2006.

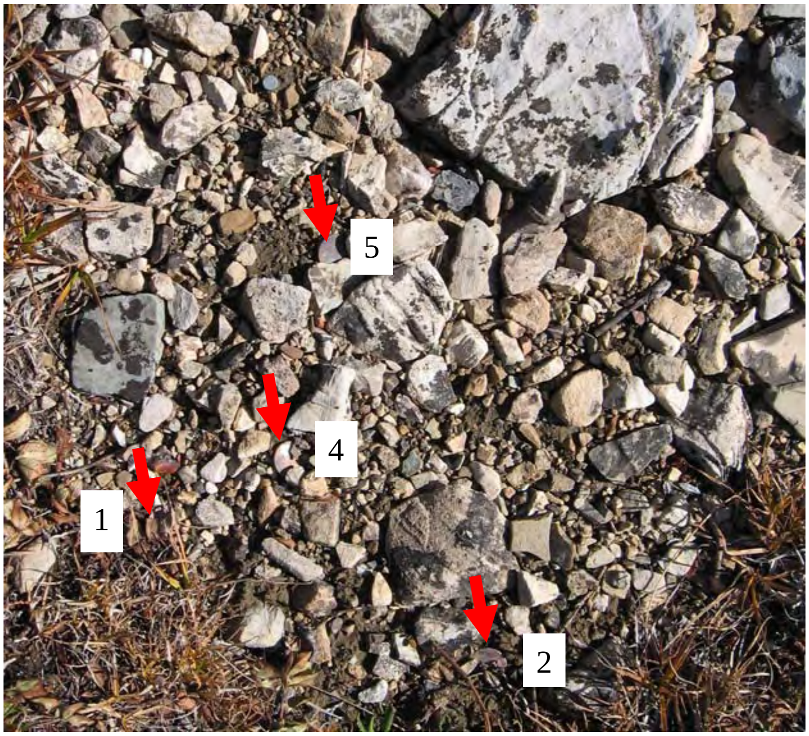


Figure 36. Site 2, DMS, September 2006.
Four pennies are still visible (arrows). No surface sorting is evident.

Marker movement

Ninety pennies were observed at 6 sites, beginning at Sites 1 and 2 in 2003. Observations of penny movement ended in September 2006. Changes were observed in the pennies positions at every site. Pennies were lost at every site but one (Site B at DMN). Penny burial occurred to over half the pennies one year after they were placed at Site A (Big Lip, DMN) but at Site 1 (Hoofprint, DMS) pennies were gradually lost in between each site visit over the three years of observation. Observing pennies resting at a vertical angle was frequent at Site 3 (Porkchop, DMS) whereas measurable lateral movement was found at Site I (Rachel, SP).

Penny movement data was collected through field notes and photographs. Pennies that could not be found were termed as “lost” rather than buried or missing from the site. Although it is probable that the pennies were completely buried by sediment and clasts given the near-burial condition in which some of the pennies were found during visits, no attempt was made to find them. Data collected from penny movement were categorized by clast and sediment burial of the penny, lateral movement of each penny across the surface, overturning (from Lincoln's Memorial to Lincoln's Profile and vice versa) of each penny, and the vertical position of each penny. The four categories were classified further into two to four subcategories depending on the amount of information obtained from field notes and the photographs. These subcategories are described in Appendix F with the data for the pennies, broken down by site, following in Appendix G through Appendix L. Each site is discussed individually below and includes a table summarizing penny movement at the site.

Site 1 (Hoofprint), DMS. Established 2003

At the end of September 2006, 10 of the 15 pennies placed in the Site 1 pan in 2003 could not be located. The loss of the pennies was documented through four site visits from 2004 to 2006 (Appendix G, summarized in Table 12). As illustrated in Figure 37, the lost pennies were not from one particular location in the pan, nor were they all lost between two flanking site visits, nor did pennies nearer each other disappear between the same site visits. Two pennies (numbers 2 and 11) have not been found since they were placed in the pan in 2003. Two other pennies (numbers 5 and 14) were found during the first two site visits (2004 and 2005) but were not located during the 2006 visits. Three pennies (4, 6, and 10) were only found once during the four site visits (in 2005 for penny 4, July 2006 for penny 6, and 2004 for penny 10). Pennies 8 and 15 have not been located since 2005. Penny 8 was placed in miniature sorted circles (approximately 3 cm in diameter) in 2003 (Figure 38). It was found twice more (in 2004 and 2005), both times the penny was vertical and wedged between clasts. Penny 9 was observed in July 2006, buried in sediment and nearly obscured in clasts (Figure 39) but was not found in September 2006.

Table 12. Summary of penny data, Site 1, DMS.

Variable	Number of pennies*			
	7-2004	**8-2005**	**7-2006**	**9-2006**
Number located	10	10	7	5
Number buried	9	10	6	4
Number laterally moved	10	2	2	0
Number overturned	2	2	2	2
Number vertically tilted	9	8	7	5

*Data summarized from Appendix G

All but one penny (number 3) was found buried in clasts or fine grained sediment during the site visits. For instance, penny 12 was partially buried by clasts and sediment by the time of the 2004 site visit (Figure 40). Penny burial did not occur on a progressive scale, becoming increasingly buried at each site visit, but rather occurred randomly. For example, penny 7, lying on the surface in 2004, was partially buried by clasts in 2005 (see Figure 25). In another instance, penny 5 was partially buried in 2004, less buried in 2005, and not found thereafter (Figure 26 through Figure 31).

Lateral movement was confirmed using repeat photographs, and occurred in all of the pennies found in 2004 (see Figure 37). Most of the movement occurred between 2003 and 2004. For instance, penny 12, between 2003 and 2004, moved across the surface and came to rest in the gutter of clasts on the edge of the sorted circles (Figure 40). Only penny 13 exhibited any visual movement after 2004 (Figure 41). During the 2004 visit, penny 13 was entrained with clasts and sediment in a miniature frost boil-like feature. The boil was no longer visible in 2005, and the penny and surrounding clasts re-settled into new positions.

Evidence of overturning from Lincoln's Memorial to Lincoln's Profile and vice versa was only observed four times since 2003. In 2004, two pennies (numbers 1 and 14) were resting with Lincoln's Profile facing up. Four other pennies (numbers 8, 9, 10, and 13) were at a vertical or near-vertical angle and determining the "side" of the penny facing up was deemed irrelevant. Poor photographic quality (penny 13) and being covered by clasts (penny 15) prevented determination of the sides of those pennies. The third penny (number 5) overturned between 2004 and 2005 (see Figure 27 and Figure 28). The fourth penny to overturn was observed in July 2006, when penny 3 was found for the first time since 2003, with Lincoln's Profile facing up (see Figure 25).

As illustrated using elongated circles in Figure 37, the pennies were rarely observed resting completely on the surface of the pan. Six pennies (numbers 4, 6, 8, 9, 10, and 15) were observed at vertical angles exceeding 66% during the visit immediately preceding the visit in which they could not be located. Three pennies (numbers 4, 6, and 10), found only once since 2003, were all resting at a vertical angle over 66%. In the instance of penny 6, it was also deeply buried and mostly hidden underneath clasts during the July 2006 site visit (Figure 30), making it difficult to locate. Most likely, it was obscured by clasts that shifted before the last site visit. Six pennies (numbers 3, 5, 7, 12, 13, and 15) changed vertical positions between observations. Like the rate of burial, the angle of repose of pennies did not increase through time. For instance, penny 13 was resting almost 90° vertically in 2004, then the angle decreased in 2005 and again in July 2006, then the angle increased in September 2006 (Figure 41).

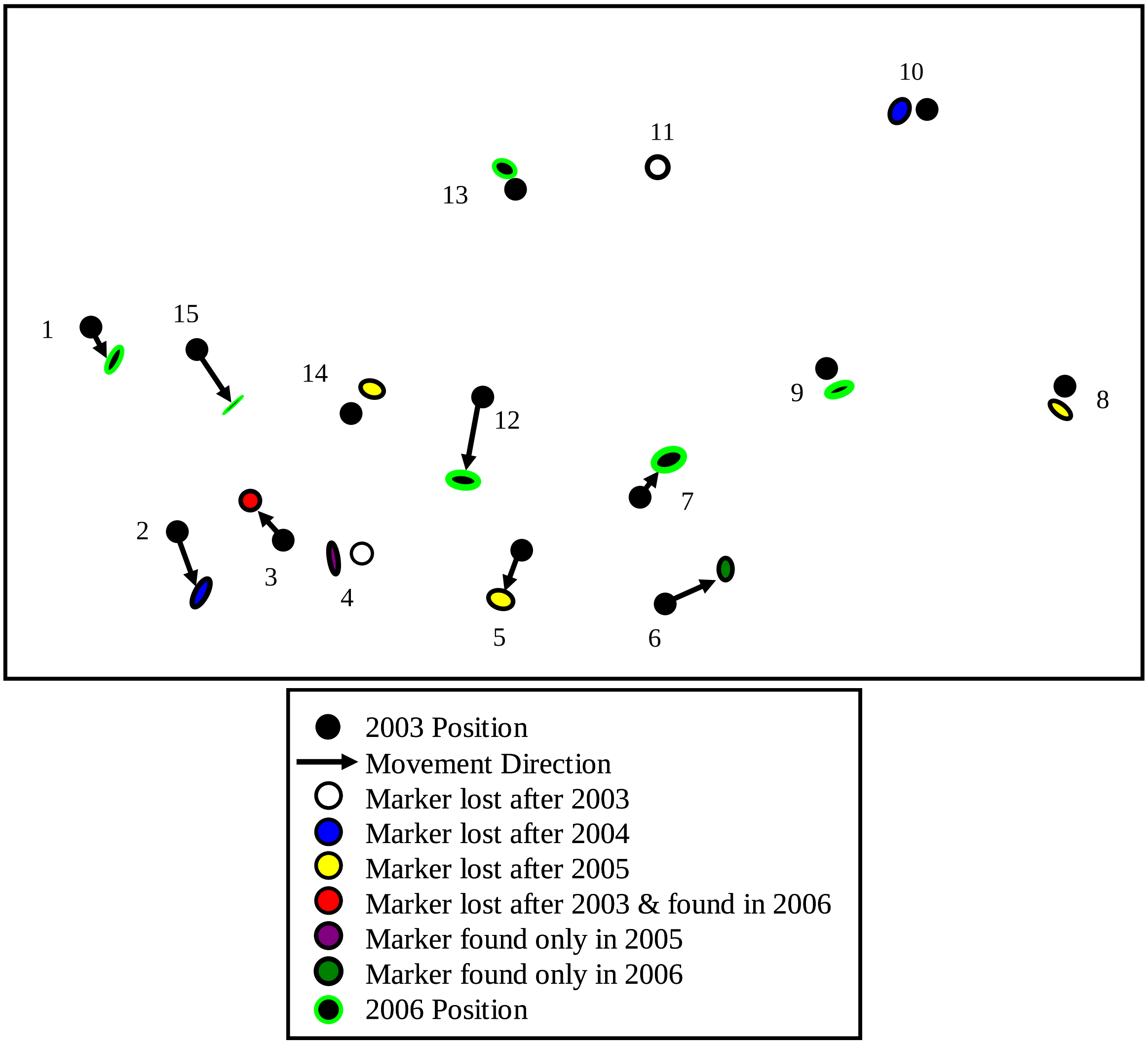


Figure 37. Diagram of penny movement at Site 1 (Hoofprint), DMS.

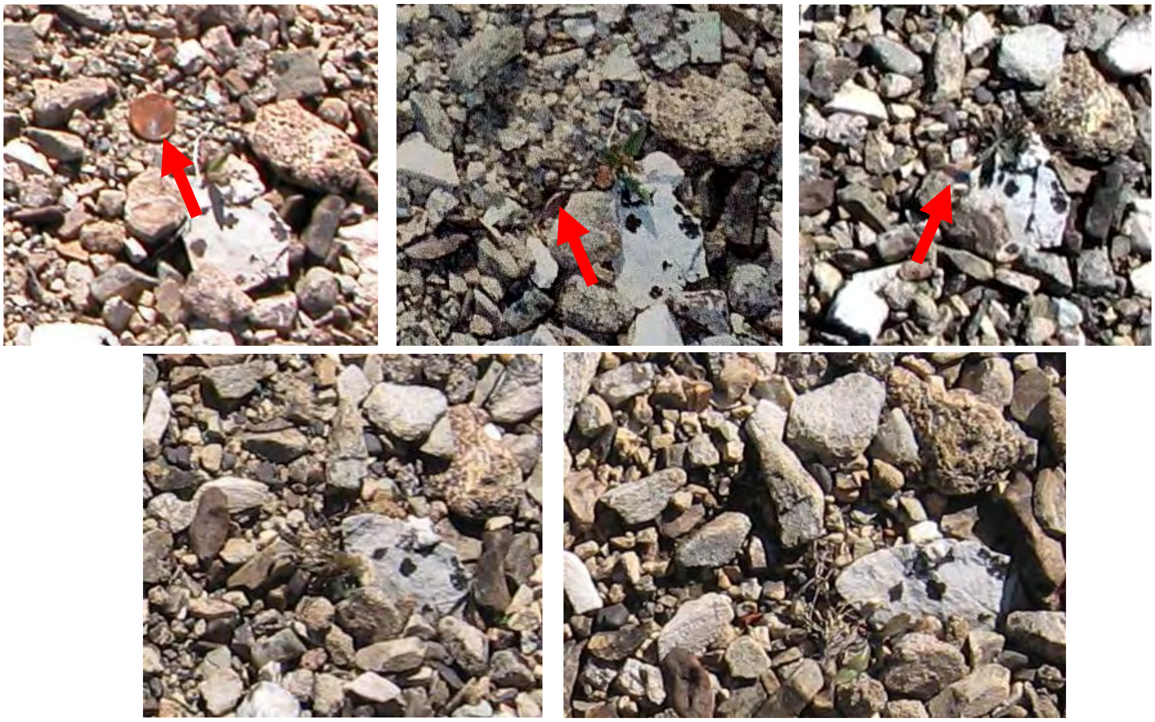


Figure 38. Penny 8, Site 1, DMS.
From L to R: upper row: 2003, 2004, 2005; lower row: July 2006; September 2006.
Penny not found in either July or September 2006.

Figure 39. Penny 9, Site 1, DMS, July 2006.

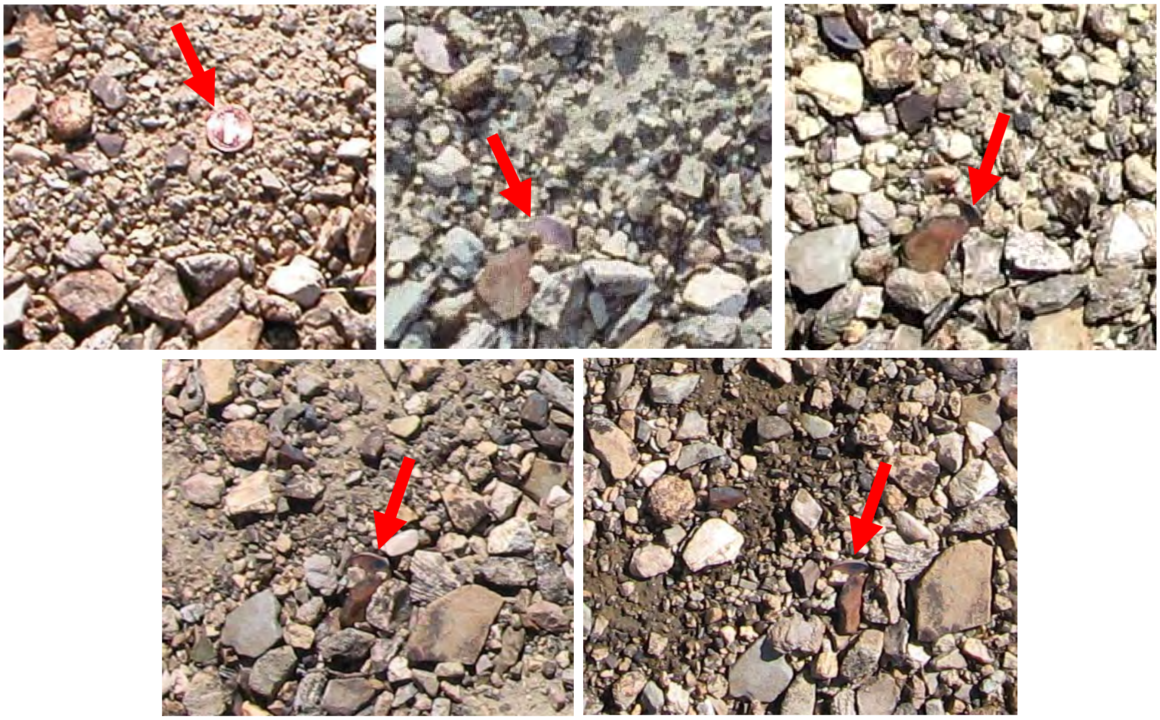


Figure 40. Penny 12, Site 1, DMS.
From L to R, upper row: 2003, 2004, 2005; lower row: July 2006, September 2006.

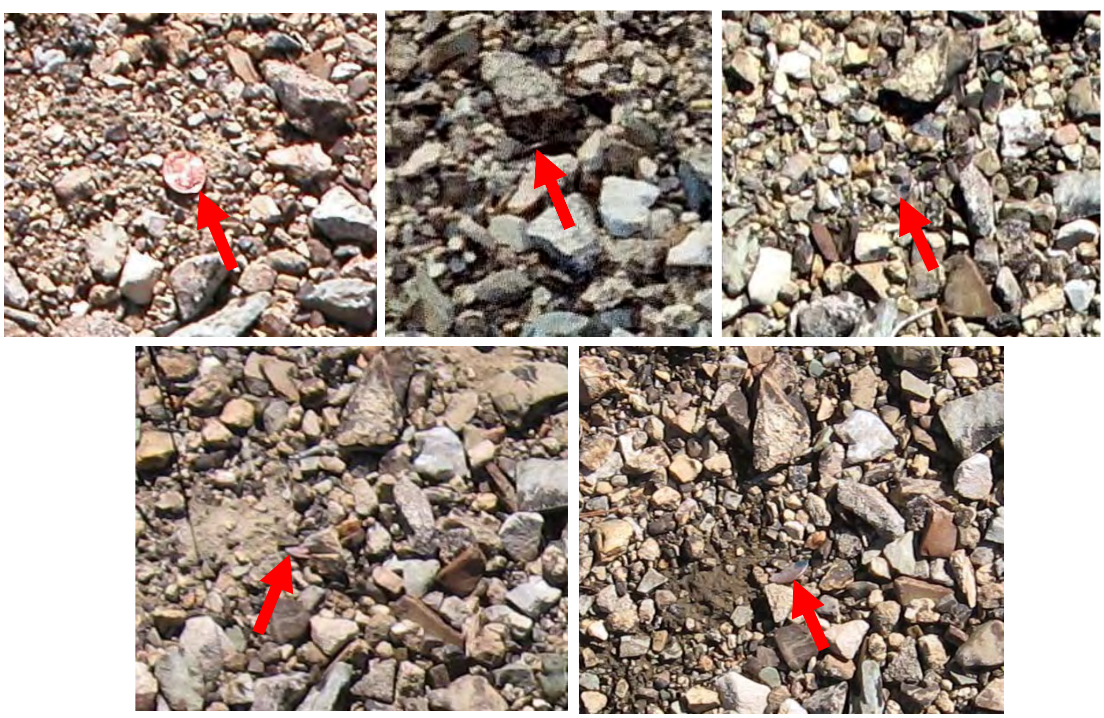


Figure 41. Penny 13, Site 1, DMS.
From L to R, upper row: 2003, 2004, 2005; lower row: July 2006; September 2006.

Site 2 (Deranged), DMS. Established 2003

At the end of the observation period, 8 of the 15 pennies placed in the Site 2 pan in 2003 could not be located (Table 13). The loss of pennies occurred throughout the observation period, in different areas of the pan and in different micro-environments (e.g. sorted gravel centers vs. fine grained sediment). Two pennies (numbers 6 and 12) have not been seen since they were placed in 2003. Both of these pennies were put into centers of sorted gravel centers (e.g. Figure 21). Two pennies (numbers 3 and 13) were only visible in 2004. Penny 3 was placed near the pan's edge, whereas penny 13 was located inside the pan. Pennies 10 and 11 were lost between the 2005 and July 2006 visit. The final two pennies (numbers 8 and 14) were not located in September 2006. Figure 43 shows the initial location of pennies 9 through 14 to illustrate the spatial distribution of the pennies not included in Figure 42. Penny 8 is not included in the diagram or photograph because it was placed the on the edge of the pan several centimeters to the right of penny 15 (see Figure 42) and several centimeters south of penny 9 (Figure 43). Including it in the diagram would have required the entire diagram less than half the

Table 13. Summary of penny data, Site 2, DMS.

Variable	**Number of pennies***			
	7-2004	**8-2005****	**7-2006**	**9-2006**
Number located	13	8	9	7
Number buried	5	6	9	7
Number laterally moved	9	8	6	2
Number overturned	6	5	4	3
Number vertically tilted	10	5	7	5

*Data summarized from Appendix H
**Data incomplete (see Appendix H)

size it is at present in order to accommodate adding penny 8 at its approximate location in the pan. Only 2 photos are available of penny 8, one of which is blurred due to camera malfunction. The other photo is from July 2006 (Figure 44).

Every penny experienced some type of burial during the observation period. However, pennies were rarely observed to be buried deeply, despite losing over half of the pennies during the observation period. Penny 7 was over 66% buried in sediment observed in 2004 (Figure 45). All subsequent site visits found the penny to continue to be buried, but to a lesser degree (e.g. Figure 45). After laying on the surface for 2 years, penny 2 was found in July 2006 to be deeply buried in sediment. At the September 2006 visit, penny 2 was more visible and less buried. No other pennies were observed to be buried beyond 66% during site visits.

Lateral movement was minimal at Site 2, with penny 1 changing its position the greatest distance between site visits in 2003 (Figure 32) and 2004 (Figure 33). Five pennies (numbers 1, 2, 5, 7, and 9) did not move, laterally, between July 2006 and September 2006.

Penny 2 overturned at least twice during the observation period as it was found in 2004 with Lincoln’s Profile facing up (Figure 33), and then in 2006 with the Memorial facing up (Figure 35). Two pennies (numbers 1 and 2), overturned between 2003 and 2004; then subsequently they were always observed with Lincoln’s Memorial facing up. Pennies 14 and 15 were found overturned 2 and 3 years after placement, respectively. Changes in the direction of the tilt of the penny were documented in two pennies. Between 2004 and 2005, penny 7’s direction of vertical tilt changed by almost 180° (Figure 45). For penny 15, the penny was at a near 90° angle in 2004 (Figure 46); but in

2005, it was resting at a high angle and facing away from the camera. By July 2006, the direction of vertical tilt changed to face away from the camera. The directional tilt was maintained for September 2006.

Fourteen times during the four site visits, pennies were observed resting at angles over 66% (see Appendix H). Five pennies (numbers 3, 8, 11, 13, and 14) were positioned at high angles on the pan's surface during the site visit immediately before visual absence was noticed. Pennies 1, 2, and 4 were observed resting flat or at a low angle (under 33%) on the pan's surface throughout the observation period.

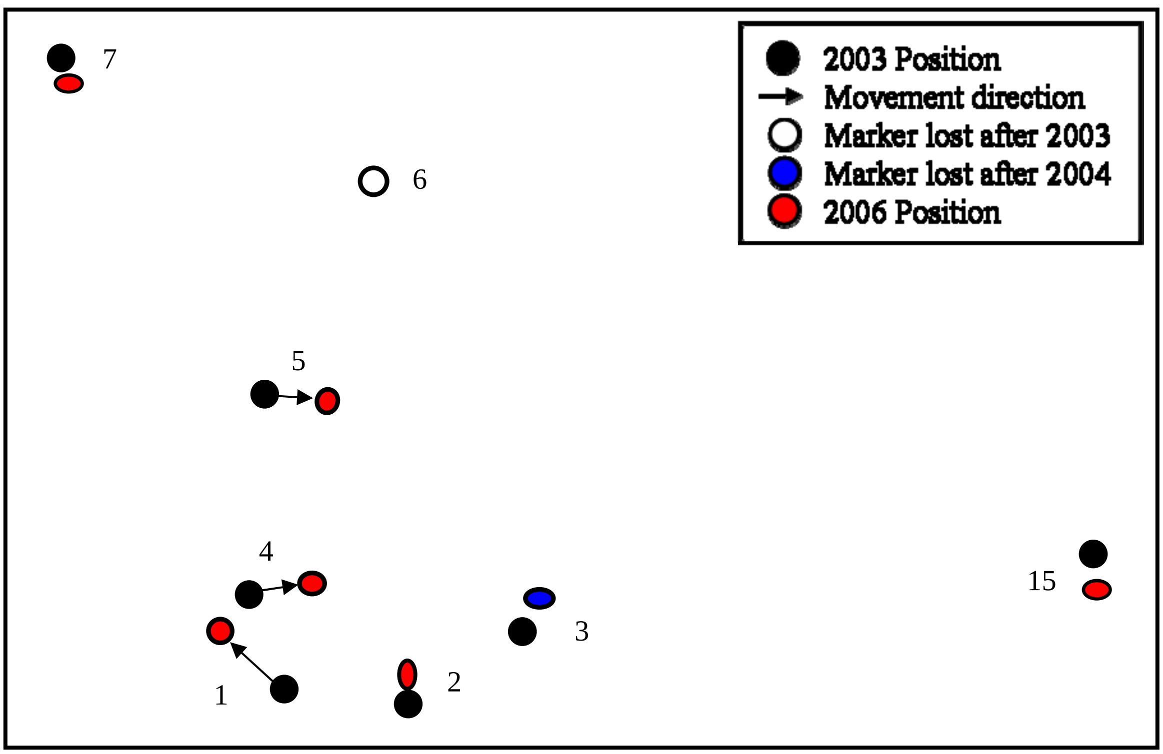


Figure 42. Partial diagram (7 of 15 markers), Site 2 (Deranged), DMS.

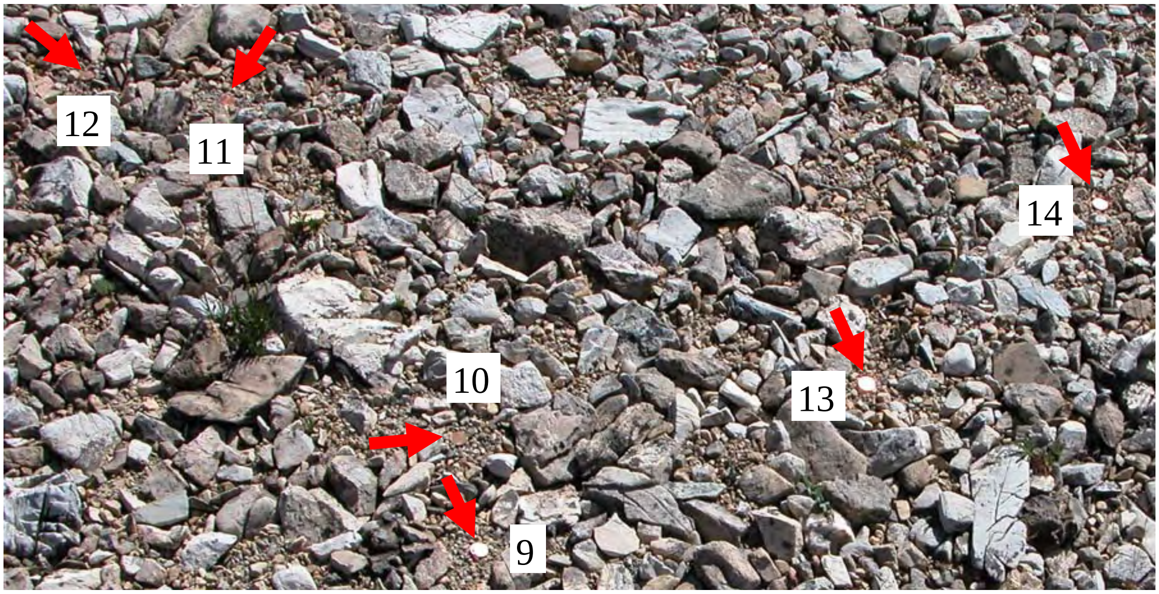


Figure 43. Photograph of pennies 9-14, Site 2, 2003.

Figure 44. Penny 8, Site 2, DMS, July 2006.

Figure 45. Penny 7, Site 2, DMS.
Penny’s direction of tilt changed from 2004 (L) to 2005 (R).

Figure 46. Penny 15, Site 2, DMS.
From left to right, upper row: July 2004 (photo is blurry); August 2005;
lower row: July 2006, September 2006.

Site 3 (Porkchop), DMS. Established 2004

Throughout the observation period, the fewest number of pennies were lost at Site 3 versus Sites 1 or 2 (Appendix I, summarized in Table 14). Penny 15 was not found during the May 2005 site visit; however, the penny was located 2 months later (and has been seen at every subsequent visit), partially covered by a single clast. Three other pennies (numbers 10, 12, and 13) were not found during either site visit in 2006 (Figure 47 and Figure 48). Pennies 12 and 13 were relatively close to each other. All three pennies were positioned near the pan edge.

All pennies, with the exception of penny 2, were buried to some extent during the observation period. Changes in the amount of a penny's burial between site visits

Table 14. Summary of penny data, Site 3, DMS.

Variable	Number of pennies*			
	5-2005	**8-2005**	**7-2006**	**9-2006**
Number located	14	15	12	12
Number buried	6	10	9	9
Number laterally moved	8	9	6	4
Number overturned	8	8	6	4
Number vertically tilted	9	9	8	10

*Data summarized from Appendix I

occurred moderately, progressing up or down a single level between site visits, (e.g. going from level one with 33% or less buried, to level two with 33-66% buried). Two exceptions were pennies 1 and 3, whose burials increased to over 66% between 2005 and 2006. Penny 1 was observed to be buried less than 33% in August 2005 and penny 3 was not buried at all (Figure 49).

At least one instance of lateral movement by each penny was observed during the observation period. Three pennies (numbers 9, 11, and 14) moved or shifted between each site visit. Although each penny moved at least once, as Figure 47 illustrates, substantial across-surface movement was minimal.

Pennies at Site 3 typically had the same penny face showing for two or more site visits. Two pennies (numbers 5 and 11) had Lincoln’s Memorial facing up during all site visits, whereas three pennies (numbers 2, 8, and 9) flipped from Lincoln’s Memorial to Lincoln’s Profile at some point between the time of placement to May 2005. Thereafter, all three pennies were found with Lincoln’s Profile facing up. Penny 7 was the only one to flip sides between 2005 and 2006 (Figure 50). Another penny (number 14) flipped back from Lincoln's Profile to the Memorial side either between the two 2005 visits or between the 2005 and 2006 visits, but a glare off of the penny (classified as poor photo quality in Appendix I) prevents further determination.

Each penny at Site 3 was observed, during at least one site visit, to be resting at a vertical angle, with the exception of penny 5, which was laying flat on the surface during all visits. Seven pennies (numbers 1, 3, 4, 6, 8, 9, and 15) were observed, at least once, at a high angle (i.e. over 66%); however, no penny sustained that angle for all four site visits. The pennies did not progressively increase their angles of tilt from horizontal through the observation period, but rather progressively increased or decreased their vertical tilt. Exceptions to this progressive change in vertical tilt were pennies 3 and 8, and are discussed in the next paragraph.

Unlike at Sites 1 and 2, Site 3 allowed season photographic comparison of penny movement. Eight pennies (numbers 1, 2, 3, 5, 6, 8, and 9) had no change in the degree of burial between May and August 2005. The burial of six pennies (numbers 1, 2, 5, 8, and 14) was unchanged between July and September 2006. Penny 1 experienced no apparent change in burial during both sets of seasonal site visits; however, between 2005 and 2006, its burial increased from < 33% to > 66%. Nine pennies (numbers 2, 5, 6, 9, 10, 11, 13, 14, and 15) moved or shifted laterally from their May 2005 positions by the time the site was revisited in August. Between July and September 2006, seven pennies (numbers 2, 5, 8, 9, 11, 14, and 15) moved or shifted laterally.

As mentioned in the Methods section, pennies resting at a high tilt were not included in the data on overturning. However, changes in the vertical positions of four pennies at DMS between July and September 2006 were dramatic, and as an example, the movement of one of the four pennies is presented here. As Figure 52 illustrates, in July 2006, penny 6 (Site 3) was slightly tilted with Lincoln's Profile facing up. By September 2006, the penny had risen over 90° and was leaning against clasts in a high angle of repose with the Memorial facing out. No other pennies overturned between either set of seasonal visits, with the possible exception of penny 14 (as previously discussed, it captured the sun's glare in the August 2005 photo). Two pennies (numbers 3 and 8) changed their vertical position dramatically between May and August 2005. Penny 3, laying flat in May, was tilted vertically at over a 66° angle in August (Figure 49). The opposite occurred for penny 8, going from a high (over 66°) angle, leaning against a clast, in May to lying flat on the surface in August (Figure 51). Four other pennies (numbers 4, 10, 12, and 14) changed vertical angles of rest between May and August (e.g. Figure 48), but not as dramatically as pennies 3 and 8. Five pennies (numbers 4, 6, 7, 11, and 14) changed vertical positions between July and September, but again not as dramatically as pennies 3 and 6 in 2005.

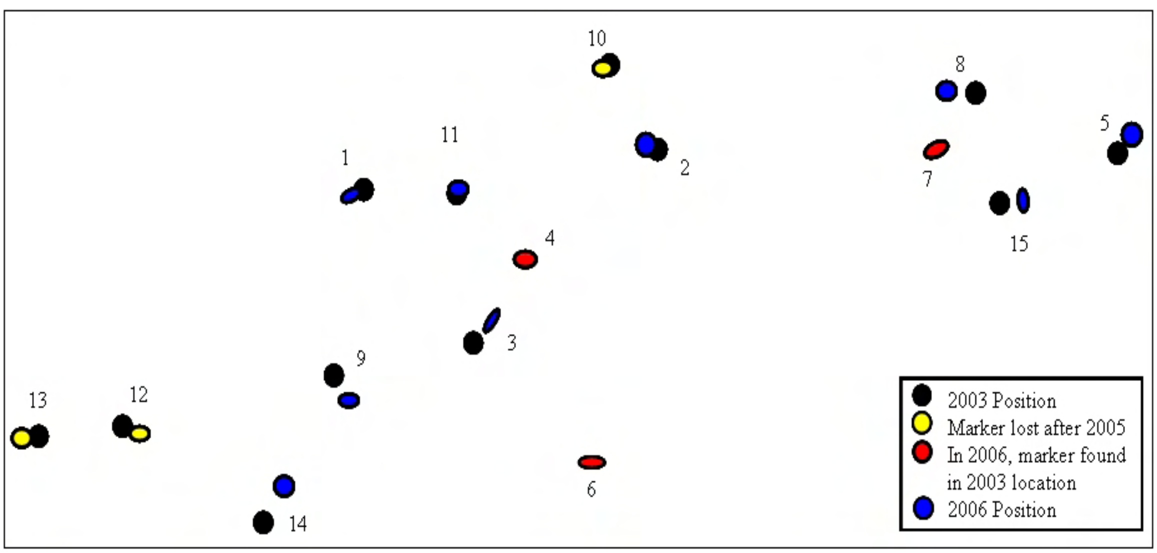


Figure 47. Diagram of penny movement at Site 3 (Porkchop), DMS.

Figure 48. Penny 12, Site 3, DMS.
From left: May 2005; August 2005; July 2006 (penny not found).

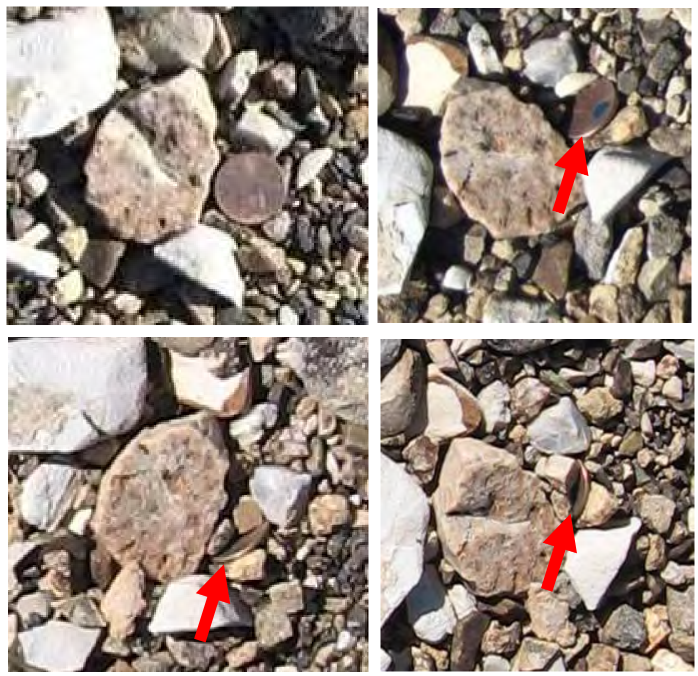


Figure 49. Penny 3, Site 3, DMS.
From left, upper row: May 2005; August 2005; lower row: July 2006; September 2006.

Figure 50. Penny 7, Site 3, DMS.
August 2005 (L) and July 2006 (R). Note penny face.

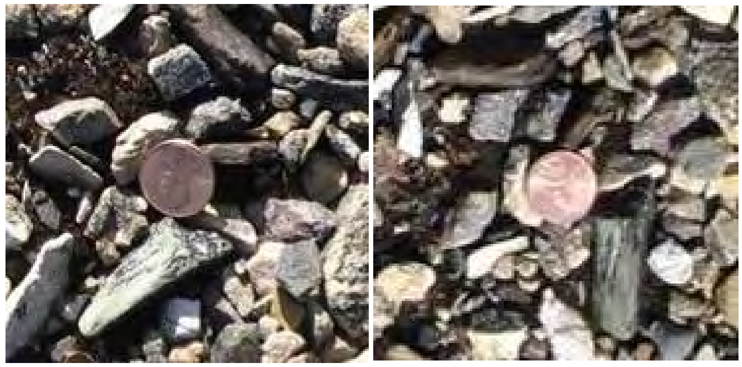


Figure 51. Penny 8, Site 3, DMS.
May 2005 (L) and August 2005 (R).

Figure 52. Penny 6, Site 3, DMS.
July 2006 (L) and September 2006 (R).

Site A (Big Lip), DMN. Established 2004

Site A at DMN was the most variable in terms of the number of pennies found during each site visit (Table 15). Eight pennies (numbers 2, 3, 4, 12, 13, 14, and 15) were not found during the first visit (2005) following the placement of the pennies in 2004. Approximately 6 weeks later (September 2005), the number of pennies not located decreased to 5 from the previous eight not observed in August 2005. Twenty-two days later, one more of the eight was found (the presence of the other four could not be

Table 15. Summary of penny data, Site A, DMN.

Variable	Number of pennies*				
	8-2005**	**9-2005****	**10-2005**	**7-2006**	**9-2006****
Number located	7	9	3	15	14
Number buried	4	7	3	13	11
Number laterally moved	3	3	0	2	3
Number overturned	0	0	0	2	3
Number vertically tilted	3	5	3	12	11

*Data summarized from Appendix J
**Data incomplete (see Appendix J)

confirmed because of snow accumulations in the pan). During the following two site visits (July and September 2006), all the pennies were found, with the exception of penny 12, whose general location in the pan was not photographed in September 2006.

Only 2 pennies (numbers 1 and 5) have remained unburied during the observation period (Figure 53). Burial occurred on 2 distinct levels: those pennies experiencing high amounts of burial or those pennies rarely buried. For instance, pennies 8 and 9 were buried before the site was visited in August 2005 (Figure 54). Since 2004, they have remained buried, but were less buried in both July and September 2006 (Figure 54). Penny 5 is an example of a penny that experienced little to no burial, as it remained easily visible on the pan's surface at each site visit (Figure 55). A more progressive burial occurred in the case of penny 7. The only portion of the penny remaining visible in September 2006 was the penny's rim (Figure 56).

Minimal lateral movement of the pennies occurred during the observation period. Pennies 8 and 9 (Figure 54) moved in opposing directions within the first year of placement, coming to rest in their present locations. No penny exhibited lateral movement during two consecutive site visits.

Evidence of overturning was seen in only one penny during the observation period. Penny 5 overturned between September 2005 and July 2006 (it was under snow during the October 2005 visit) (Figure 55). No other pennies were found with Lincoln's Profile facing up.

Eight pennies (numbers 3, 7, 8, 9, 10, 12, 14, and 15) found at least once during the observation period, were tilted at a high angle. Pennies 8 and 9 had the same vertical tilt at each site visit (Figure 54). Pennies 5 and 6 are typical pennies resting at low angles (Figure 55).

Vertical tilt and burial of the pennies were the most frequent changes observed. Changes in a penny's position between seasons were minimal. Two seasonal visits were completed at Site A, between August and September 2005 (a 22-day interlude), and July and September 2006 (a 75-day interlude). Two pennies (2 and 3) were found in September 2005 that had been not located during the August visit. Between July and September 2006, changes could be seen in the condition of the two pennies. In September 2006, pennies 2 and 3 had less sediment covering them. In the case of penny 3, the penny was still tilted but the surface was more exposed. Less than a fourth of the surface of penny 2 was showing in July 2006; however, by September, a third of the penny was exposed. (Figure 57), but it remained at the same depth below the pan's surface.

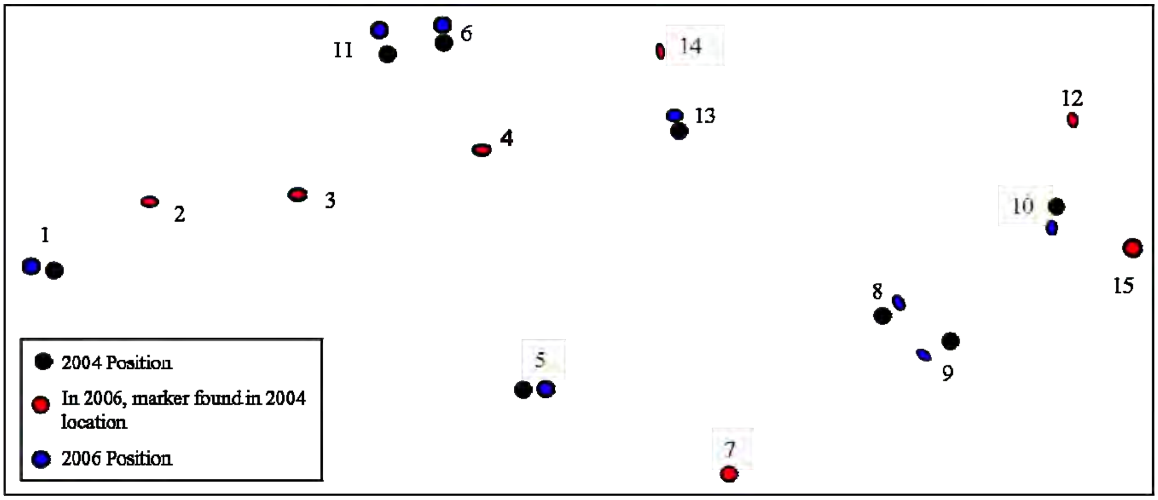


Figure 53. Diagram of penny movement at Site A (Big Lip), DMN.

Figure 54. Pennies 8 and 9, Site A, DMN.
Left to right, upper row: 2003 (photo is blurry), August 2005;
lower row: July 2006; September 2006.

Figure 55. Penny 5, Site A, DMN.
Penny overturned between 2005 and 2006.
From L to R, upper row: August 2005; September 2005;
lower row: July 2006; September 2006.

Figure 56. Penny 7, Site A, DMN.
From L to R, upper row: August 2005; September 2005;
lower row: July 2006; September 2006.

Figure 57. Penny 2, Site A, DMN, July (L) and September 2006 (R).

Site B (George), DMN. Established 2003

Site B is a small pan located down slope from Site A (Big Lip). The site was one of three sites established in 2003 (Sites 1 and 2, DMS, are the other ones). Photographs of the original location of the pennies placed in the pan were not available; therefore, a diagram could not be constructed illustrating the movement of the pennies over time. A map was drawn to illustrate the spatial distribution of the pennies (Figure 58).

The fewest number of pennies were lost at Site B compared to all the Divide Mountain sites (see Table 11). Site B was visited three times since it was established in 2003. During those visits, only once was one penny (number 11) was not located (in July 2006) (Table 16). The penny was found on a subsequent September 2006 visit (Figure 59). The penny was not buried or tilted vertically into the ground when the site was visited in 2004.

Partial burial was experienced by all the pennies at Site B, particularly in 2006. In 2004, all buried pennies had 33% or less of their surface covered, with nine pennies (numbers 3, 7, 8, 9, and 10-14) not buried at all. In July 2006, however, eight pennies (numbers 1, 5, 6, 8, 9, 12, 14, and 15) were buried at least 33%. Nine pennies

Table 16. Summary of penny data, Site B, DMN.

Variable	Number of pennies*		
	7-2004**	7-2006	9-2006
Number located	15	14	15
Number buried	5	14	15
Number laterally moved	**	**	2
Number overturned	5	6	6
Number vertically tilted	5	11	13

*Data summarized from Appendix K.
**Data incomplete (see Appendix K)

(numbers 1, 3, 5, 9, 10, and 12-15) also had 33% or more of their surface covered in September 2006.

Data for lateral movement determination were limited (see the Methods chapter for further information), with only two pennies (numbers 5 and 11) showing any signs of lateral movement. This lateral movement occurred between July and September 2006. In 2004, five pennies (numbers 2, 3, 4, 8, and 9) had overturned and Lincoln's Profile was facing up. When the site was visited in July 2006, only penny 8 still had Lincoln's Profile facing up, the other four pennies had the Memorial facing up. Four other pennies (numbers 5, 6, 10, and 11) were found with Lincoln's Profile facing up in July 2006 and remained with facing "heads up" through the September 2006 visit.

Two pennies were located during the site visits resting at vertical angles over 66°. The first penny, number 9, had fallen into sediment next to a large clast and was first found in this position in July 2006 (Figure 60). The second penny (number 13) (Figure 61), like penny 9, fell into sediment with one face of the penny visible. The penny was surrounded by large clasts.

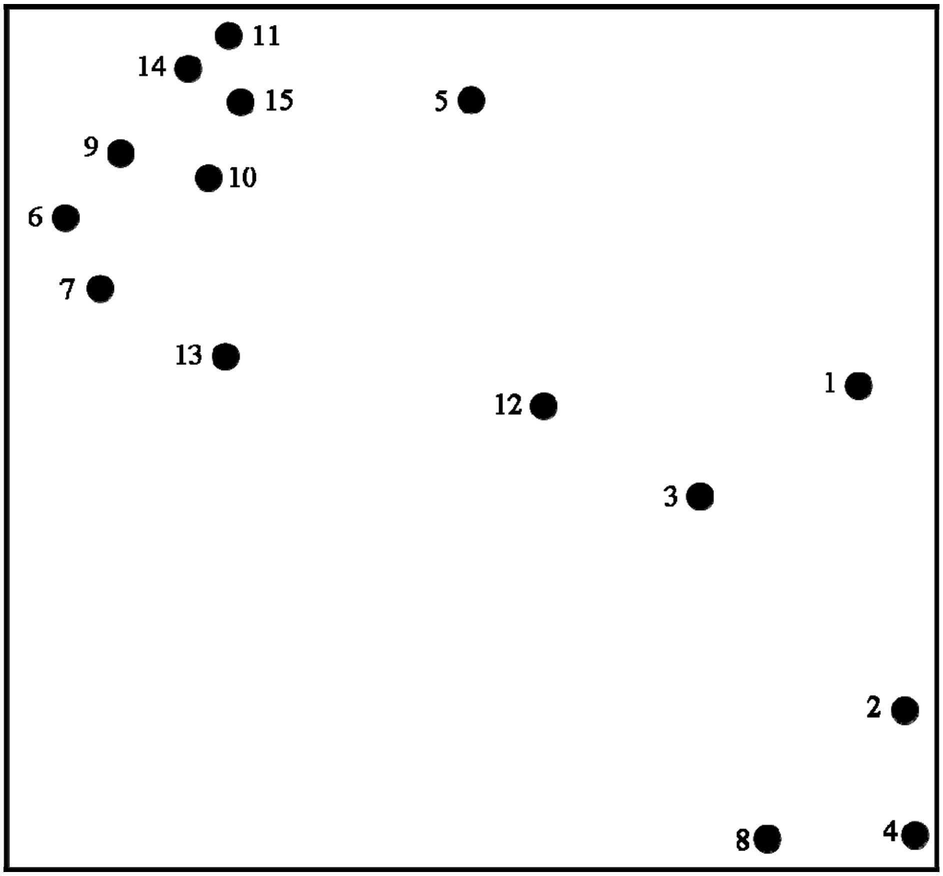


Figure 58. Map showing penny locations, Site B, DMN (not drawn to scale).

Figure 59. Penny 11, Site B, DMN, July (L, no penny) and September 2006 (R). On the left, the red circle approximates penny 11's location as it appears in September (R, red arrow). Penny 14 (blue arrow) was more visible in September 2006.

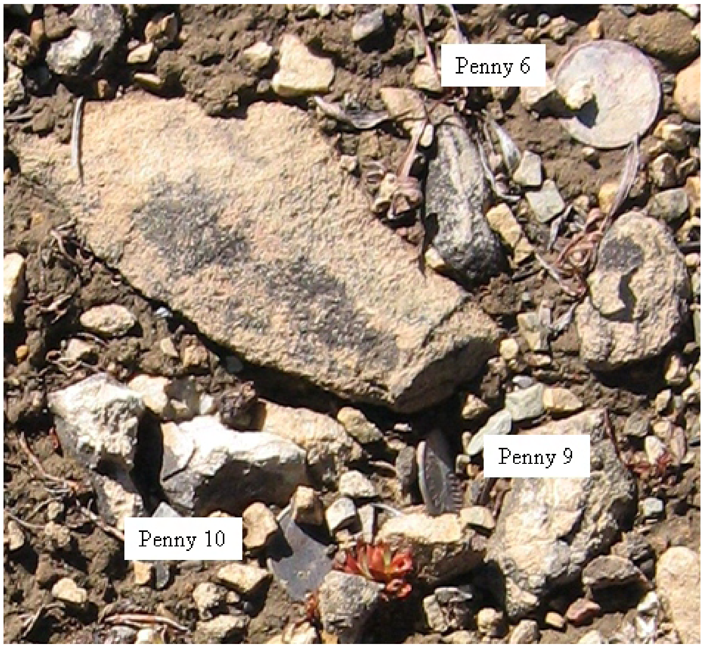


Figure 60. Site B, DMN, with pennies 6, 8, and 10, September 2006.


Figure 61. Penny 13, Site B, DMN, July 2006.

Site I (Rachel), SP. Established 2005

One year after placement, penny 8 could not be located at Site I, SP (Table 17, Figure 62). All other pennies were found. The clasts and gravel in the area where penny 8 was located had shifted and moved since the site was visited in 2005 (see Figure 63 for location of penny relative to other pennies).

Table 17. Summary of penny data, Site I, SP.

Variable	Number of pennies*
	7-2006
Number located	14
Number buried	5
Number laterally moved	13
Number overturned	6
Number vertically tilted	6

*Data summarized from Appendix L

Five pennies (numbers 4, 5, 6, 9, and 15) were found buried to some degree. The pennies were buried by clasts and gravel rather than fine-grained sediment. For example, penny 5 (Figure 64) was partially buried by a large clast and small gravel.

All the pennies underwent some lateral movement between site visits. As shown in Figure 63, lateral movement was random, with pennies not moving inward or outward in the pan. For instance, penny 2 (Figure 65) moved a noticeable amount between site visits. The photographs are offset so that rocks in both photos line up. Arrows are used in Figure 65 to note the locations of rocks visible in both 2005 and 2006 photographs. The penny was originally placed next to the rock with the red arrow. One year later, the penny was found in a position northwest of its original location and next to the rock indicated by the yellow arrow in Figure 65.

Six pennies (numbers 1, 2, 3, 4, 9, and 13) were found in 2006 laying on the surface “heads up” (Figure 65). With the exception of penny 9, the pennies that overturned were located in the upper left portion of Figure 63. Pennies located in the lower portion of the diagram (i.e. pennies 11, 12 and 13) did not overturn.

Six pennies (numbers 1, 6, 9, 10, 11, and 15) were found tilted. Only penny 15 was lying at a near 90° angle, wedged between large clasts (Figure 66). The other pennies were resting at angles lower than 30°.

Figure 62. Penny 8, Site I, SP.
2005 (L) & 2006 (R). Penny was not found in 2006.

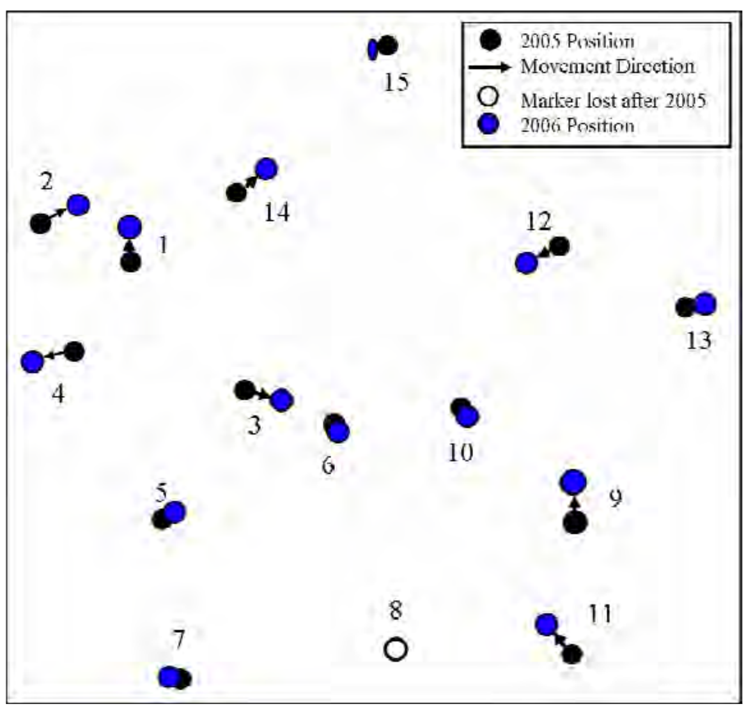


Figure 63. Diagram of penny movement at Site I (Rachel), SP.

Figure 64. Penny 5 (arrow), Site I, SP.
2005 (L) & 2006 (R).

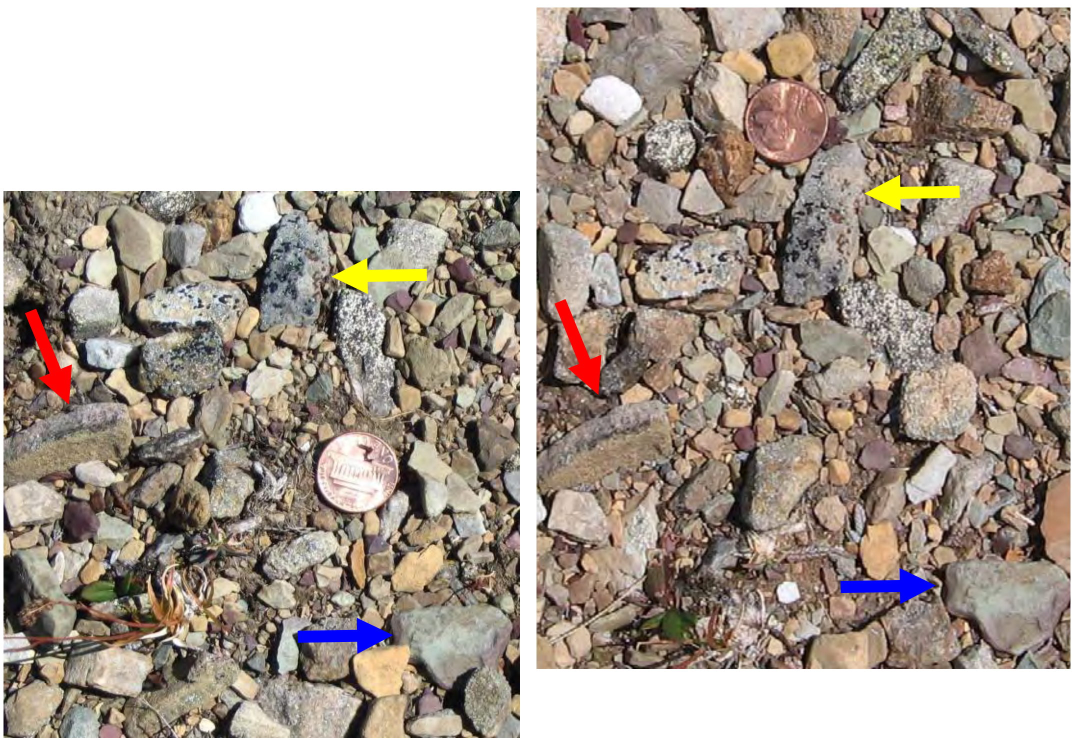


Figure 65. Penny 2, Site I, SP, 2005 (L) & 2006 (R).
Corresponding color arrows point to the same rock in both photos.
Further explanation is given in the text.

Figure 66. Penny 15, Site I, SP, 2006.

Clast movement

The movement of ninety clasts (15 at each site) was observed through repeat photography at the six study sites (Table 18). Clasts located near pennies during the first-photographed site visit were chosen so that clast size would be known, relative to the size of the nearby penny. Most of the clasts were, therefore, chosen semi-randomly from the area immediately surrounding the pennies.

In general, movement of the clasts was more subtle than the pennies, with the clasts less likely to be observed overturning to another side. Lateral shifting of clasts was

Table 18. Dates of photographs used for clast analysis.

Site	Dates of photographs					
1 (Hoofprint)	Jul-03	Jul-04	Aug-05		Jul-06	Sep-06
2 (Deranged)	Jul-03	Jul-04	Aug-05		Jul-06	Sep-06
3 (Porkchop)			Aug-05		Jul-06	Sep-06
A (Big Lip)				Oct-05	Jul-06	Sep-06
B (George)					Jul-06	Sep-06
I (Rachel)			Aug-05		Jul-06	

the most common change observed. Some of the clasts were partially buried at the beginning of the observation period. The same categories of burial that were used with pennies were applied to the clasts with the addition of negative numbers (i.e. -1, -2, and -3) to indicate that the clasts, originally buried, were less buried than when they were first observed.

Site 1, DMS. Photographed since July 2003

Changes in the positions of clasts at Site 1 were observed through photographs taken beginning in 2003, when pennies were first placed in the pan (Table 19). A photograph of each clast is located in Appendix M. The clasts chosen from this site ranged in size from approximately 1 cm (clast 15, Appendix M) to several cm (e.g. clasts 5 and 6, Appendix M). Clasts were also different colors, including green, brown, grey, and white. The clasts were located next to each of the 15 pennies placed in the pan. Photographs of the clasts were available from the four visits to the site (2004, 2005, July 2006 and September 2006), and the initial visit when pennies were placed in the pan (2003).

Table 19. Summary of clast data, Site 1, DMS.

Variable	Number of clasts*			
	7-2004	8-2005	7-2006	9-2006
Number located	15	13	13	13
Number buried	1	2	1	1
Number rotated	10	6	9	4
Number overturned	4	3	6	2
Number moved laterally	4	3	3	1

*Data summarized from Appendix N

Selected clasts were located in the photographs taken after the initial site visit and establishment in 2003. Clast 2, located near the edge of the pan, was not found in either July or September 2006. Clast 10 was not found in the August 2005 photograph. All other clasts were located. Four clasts (numbers 1, 3, 5, and 15) were already partially buried when they were first photographed in 2003. In 2004, all four were found laying on the surface of the pan. Clast 5 was again partially buried during the 2005 site visit but unburied for the July and September 2006 visits (Figure 67). Clast 15 was also observed reburied but during the July 2006 visit, when it was over two-thirds buried. Clast 15 was less buried at the time of the September 2006 visit. Clast 6 was first observed unburied in 2003, but was subsequently partially buried prior to the initial 2003 visit and the 2004 visit (Figure 68). The clast was in a state of varying amounts of burial during each site visit.

The selected clasts at Site 1 rotated the most when compared to the other Divide Mountain study sites (both north and south sites). Fourteen clasts (with the exception of clast 14) rotated at some point between 2003 and September 2006. Clast rotation was the highest between 2003 and 2004, with rotations of 15 to 110°; additionally, the most clasts rotated during this time frame than between subsequent visits. Two clasts (numbers 9 and 13) only rotated once; however, clast 13 was not found after the 2004 visit. All the other clasts rotated at least twice. Clasts 1 and 12 rotated between every visit. Clast 1 was the most active clast of the ones selected for study at Site 1, as it also laterally moved more than any other clast. Between 2003 and 2004, clast 1 rotated 15° to the left (Figure 69), and rotated an additional 35° between 2004 and 2005. The clast rotated another 15°

between 2005 and July 2006. In September 2006, the clast had not moved but had rotated approximately 5° to the left.

Few clasts overturned or changed their position vertically at Site 1. Two clasts (numbers 8 and 14) overturned between each site visit from 2003 to July 2006.

Lateral movement of the clasts was recorded during every site visit (Appendix N). Eleven clasts exhibited signs that some type of lateral movement had occurred during at least two of the four site visits made between 2003 and September 2006. For instance, clast 1, in 2003, had the appearance of having sunk into the ground (Figure 69). In 2004, the clast was laying on the surface and had moved a little towards the inside of the pan (to the right in the photo). In 2005, the clast had moved until it was laying almost on top of the partially buried penny (penny 1 for reference). Of further note, the blue-colored gravel lying on top of penny 1 in July has moved to the lower center of the photograph. By the July 2006 visit, clast 1 was laying over the penny, in addition to a small piece of gravel (an arrow is pointing to the blue-colored clast in Figure 69) that was next to clast 1 in 2005.

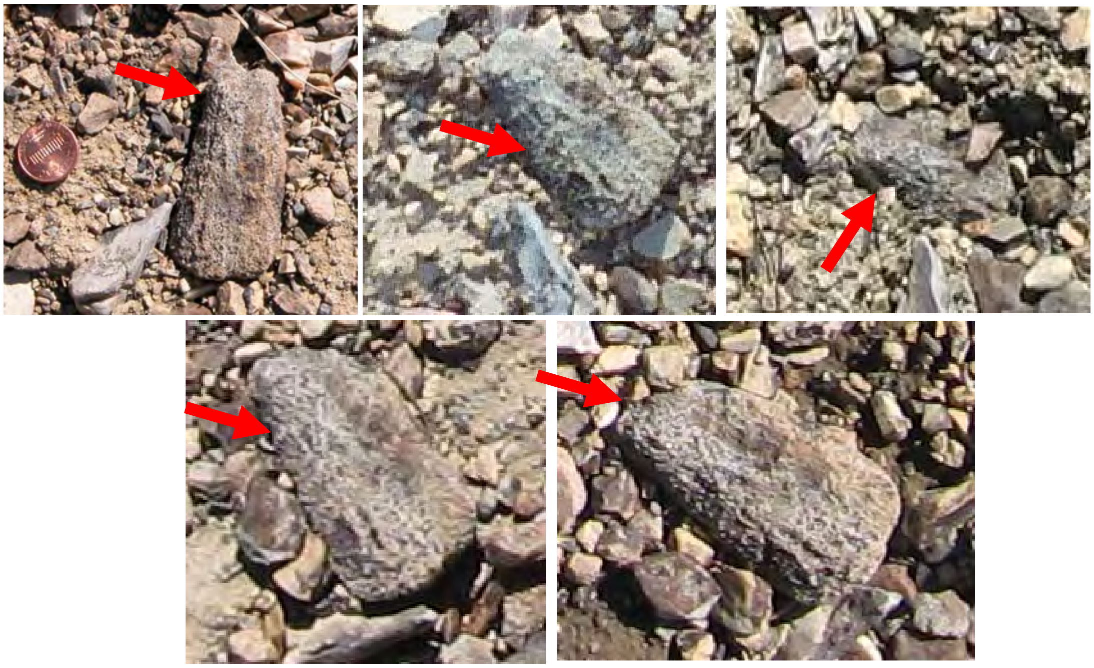


Figure 67. Clast 5 (arrow), Site 1, DMS.

From L to R, upper row: 2003, 2004, 2005; lower row: July 2006; September 2006.

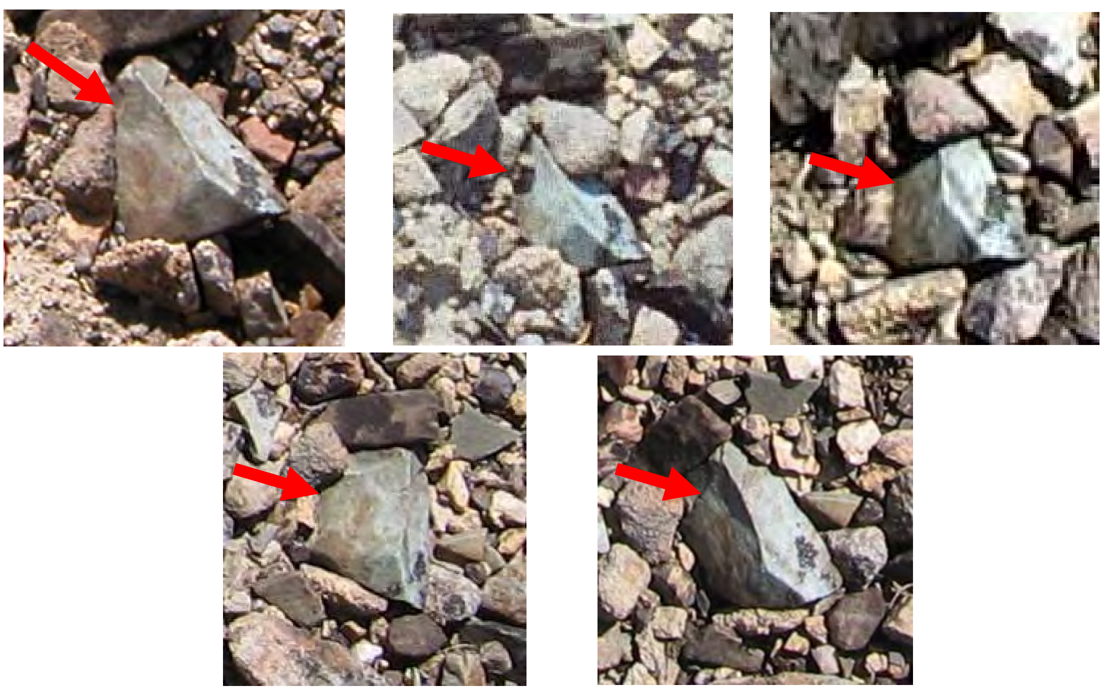


Figure 68. Clast 6 (arrow), Site 1, DMS.

From L to R, upper row: 2003, 2004, 2005; lower row: July 2006; September 2006.

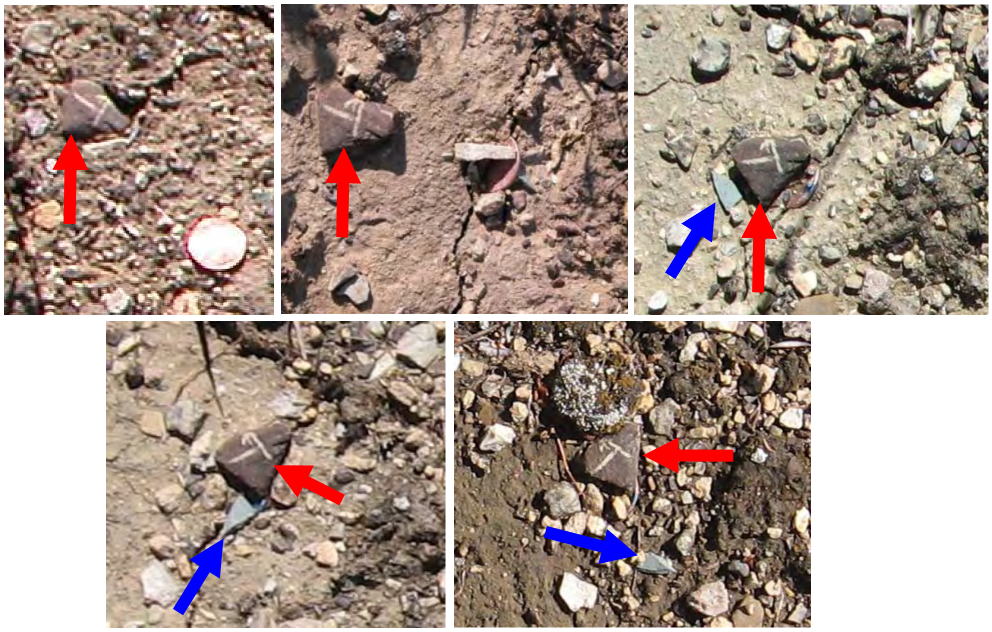


Figure 69. Clast 1 (arrow), Site 1, DMS.
From left to right, upper row: 2003, 2004, 2005; lower row: July 2006; September 2006.

Site 2, DMS. Photographed since July 2003

Selected clasts at Site 2 often rotated or moved laterally between site visits but were rarely buried (Table 20). In order to obtain a long observation period of clasts at

Table 20. Summary of clast data, Site 2. DMS.

Variable	**Number of clasts***			
	7-2004	**8-2005**	**7-2006**	**9-2006**
Number located	15	14**	15	15
Number buried	1	1	2	1
Number rotated	9	7	9	5
Number overturned	3	3	4	1
Number moved laterally	6	7	7	1

*Data summarized from Appendix P
**Photographs were unavailable for one clast in 2005

Site 2, clasts were selected from a small portion of the pan subjected to extensive photographic documentation since 2003. This part of Site 2 was the same area containing pennies 1-7 and is also the portion included in the diagram showing the distribution of pennies 1-6 (Figure 42). The clasts selected were at least 2 cm in length (Appendix O). Colors of the clasts were limited to hues of brown and grey.

Few selected clasts were buried between the site visits, beginning in 2003 and ending in 2006. Two clasts (numbers 10, and 12) were found buried on two consecutive visits (Appendix P). Between 2003 and September 2006, only one other clast (number 11) was partially buried, occurring between 2003 and 2004. When the study began in 2003, three clasts (numbers 1, 10, and 14), were already partially buried or “set” in fine-grained sediment. In 2004, all three clasts were resting on the surface, completely unburied. One of these clasts, number 10, was partially covered by a single large clast in 2005 and July 2006.

Fourteen clasts rotated at least once between 2003 and September 2006. Clast 1 rotated between each site visit and five clasts (numbers 1, 4, 7, 8, 12, and 14) rotated between three site visits. In total, nineteen rotations were towards the right whereas the other ten rotations were towards the left. Only two clasts (numbers 7 and 8) exhibited both left and right rotations. All other clasts with multiple rotations were consistently in one direction.

Few clasts appear to have overturned between 2003 and September 2006. Four clasts (numbers 1, 4, 5, and 10) overturned, each of which was observed during two separate visits to have overturned. Clasts 4, 5, and 10 overturned twice during consecutive visits. Clast 1 overturned before the 2004 visit and before the July 2006 visit.

Ten clasts changed their positions laterally between 2003 and Sept 2006. Seven of the ten clasts (numbers 2, 3, 4, 5, 8, 10 and 12) moved between two or more visits. The clasts moved less than 1 cm each time. For example, clast 2 moved between the 2004 and 2005, in addition to moving between the 2003 and 2004 site visits. In both instances the movement was slight and in the same direction. As shown in Figure 70, the clast moved towards a large rock (clast 9, green arrow) until 2005, when clast 2 was lying against clast 9. Since 2005, clast 2 stayed within 1 cm of the same position; however, it rotated so that clast 2 was lying lengthwise against clast 9. At the same time that clast 2 moved, penny 2 also moved, first away from clast 9 (blue arrow). Then, penny 2 moved closer to clast 9 and 2, becoming buried in sediment by the July 2006 visit.

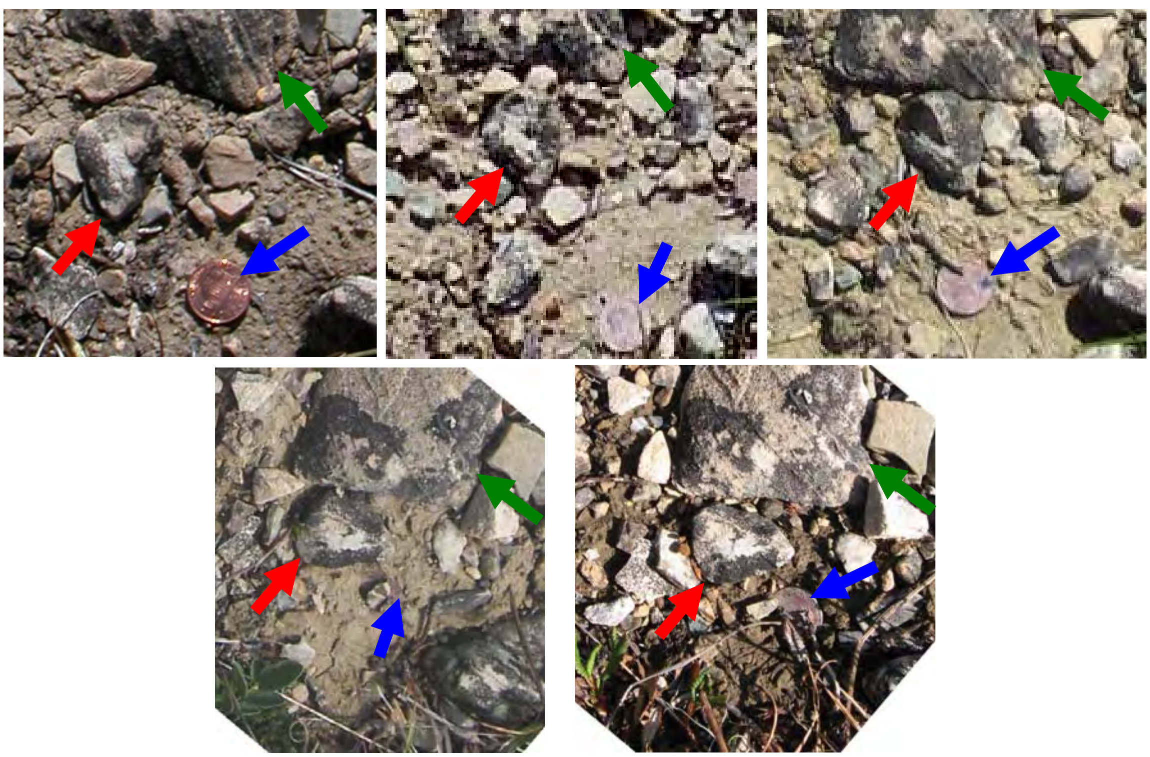


Figure 70. Clast 2, Site 2, DMS.
From L to R, upper row: 2003, 2004, 2005; lower row: July 2006; September 2006.
Red arrow: clast 2; blue arrow: penny 2; green arrow: clast mentioned in text.

Site 3, DMS. Photographed since May 2005

Clast data were obtained from photographs taken in May 2005 and continued until the September 2006 visit, resulting in data from three sets of photographs (Table 21). Selected clast sizes were a minimum of 2 cm long. Colors of the selected clasts included hues of greens and yellows (Appendix Q). The selected clasts at Site 3 experienced overturning, rotation, and lateral movement; however, burial was the most prevalent.

One clast (number 15) was not located in July or September 2006 (Figure 71). In 2005, the clast was lying on the surface, with a corner of the clast under a larger white rock (green arrow on figure). In July 2006, clast 15 was no longer visible and the larger white clast had moved across the surface to rest against a large rock (green arrow).

Table 21. Summary of clast data, Site 3, DMS.

Variable	Number of clasts*		
	8-2005	7-2006	9-2006
Number located	15	14	14
Number buried	4	8	6
Number rotated	2	3	1
Number overturned	5	6	3
Number moved laterally	2	5	4

*Data summarized from Appendix R

Complete burial of the clast probably occurred as, in September 2006, a partially buried clast with the same shape was found (red arrow in the September 2006 photograph). If the covered rock is clast 15, then it moved across the surface of the pan during the same time that penny 15 moved the opposite direction.

The selected clasts became increasing buried during each subsequent site visit. Burial may appear to decrease over time according to the numerical tabulations in Table

21; however, the positions of two clasts (numbers 12 and 13), which were partially buried in July 2006, could not be confirmed because September 2006 photographs of the clasts were not available. A photograph of clast 10 was not available from July 2006.

Four clasts (numbers 5, 10, 11, and 12) rotated a total of 6 times between May

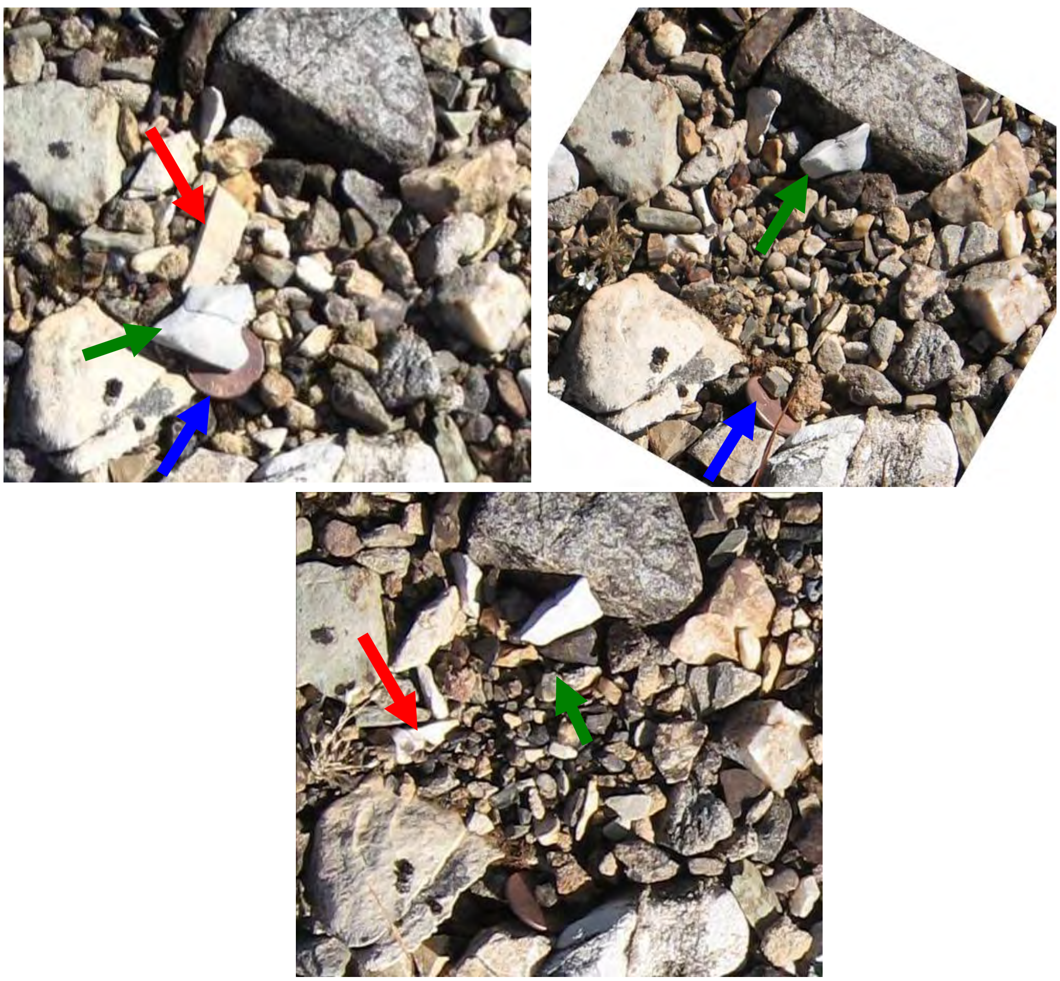


Figure 71. Clast 15, Site 3, DMS.
Red arrow: clast 15, blue arrow: penny 15; green arrow: clast mentioned in text. August 2005 (upper L), July 2006 (R) (clast not found); Lower center: September 2006 (red arrow indicates possible clast 15).

2005 and September 2006. Rotation ranged from 5 to 55°. The clasts that rotated were not spatially closer to each other than other clasts.

Four clasts (numbers 2, 4, 7, and 13) that overturned between May and August 2005 also overturned between August 2005 and July 2006. Only clast 4 had overturned between each site visit.

Lateral movement observed in the selected clasts was minimal, with only one clast (number 9) moving approximately 2 cm between August 2005 and July 2006 (Figure 72). Six other clasts each moved under 1 cm between site visits.

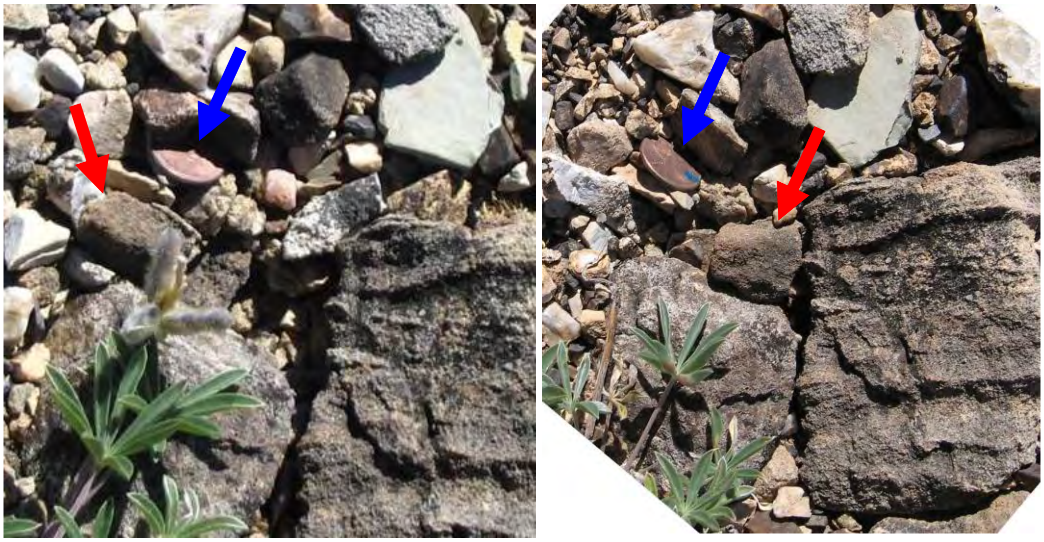


Figure 72. Clast 9, Site 3, DMS.
Red arrow: clast 9; blue arrow: penny 9. August 2005 (L) & July 2006 (R).

Site A, DMN. Photographed since September 2005

At Site A, clasts were observed 3 times beginning in September 2005 and ending in September 2006 (Table 22). The selected clasts ranged in size from approximately 1 cm to over 4 cm in length (Appendix S). Clast colors were primarily in shades of white

Table 22. Summary of clast data, Site A, DMN.

Variable	**Number of clasts***		
	10-2005	**7-2006**	**9-2006**
Number located	4	14	14
Number buried	3	9	6
Number rotated	0	2	1
Number overturned	0	0	0
Number moved laterally	0	0	0

*Data summarized from Appendix T

and beige. Very few of the clasts were found in October 2005 because of snow accumulations in the pan. Clast 12 was found in October, but was not found during the two subsequent site visits, and was the only clast not found in either of the 2006 visits.

All of the clasts, when first seen in September 2005, were in a state of burial by fine-grained sediment. The clasts were not resting on the surface but were surrounded by sediment with an unknown portion of the clast residing underneath the sediment. Clast 8 (Figure 73) provides an illustrated example of this relationship between clasts and sediment at Site A. In October 2005 (top photo), the clast (red arrow) appears to have blunt narrow ends (black arrows) with a wide and rounded center. Much of the sediment covering the clasts in the October 2005 photo was gone by July 2006 (middle photo). Clast 8 was much longer than it appeared in October 2005 and much wider with the right portion of the clast (black arrow) not yet uncovered by the sediment. Other clasts were also uncovered by the loss of sediment. The appearance of the white clast (green arrow) in the upper left corner of both the top and middle photos has changed. In the upper photo, the clast appears small, with clasts resting above it; however, as the center photo shows, the clasts were much thicker and longer than when it was first seen. This idea was confirmed by the lower photo, taken at a lower, more oblique angle than the first two photos, and shows part of the thickness of the clast. The bottom photo also shows one edge of clast 8 (lower portion of the photo), indicating that the shape of clast 8 may be thin and long. A clast not visible in October 2005 moved, by September 2006, onto part

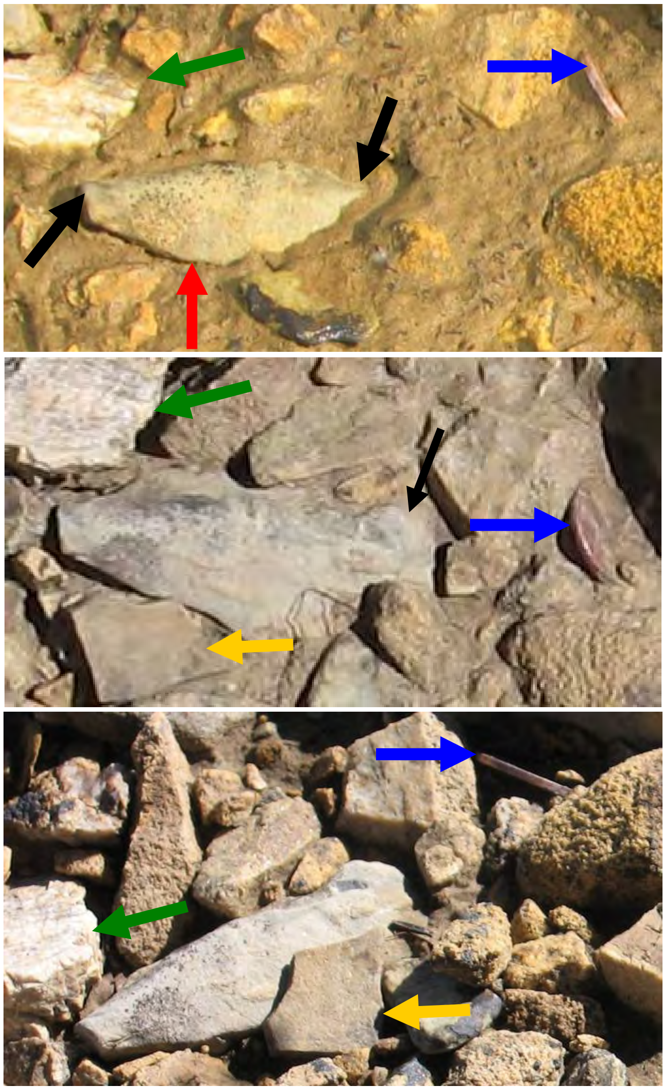


Figure 73. Clast 8, Site A, DMN.
From top to bottom: October, 2005; July 2006; September 2006.
Red arrow: clast 8; blue arrow: penny 8; Clasts noted by green and orange arrows mentioned in text.

of clast 8 (orange arrows in the center and lower photos), indicating lateral movement of clasts occurred at Site A.

In July 2006, two clasts (numbers 7 and 10) had rotated from their September 2005 positions. Their rotations were under 20°. In 2006, two other clasts (numbers 5 and 11) rotated between July and September. These clasts also rotated less than 20°. None of the selected clasts in Site A were observed to have overturned or moved laterally.

Site B, DMN. Photographed since July 2006

The observation period of clasts at Site B, DMN, was the shortest of the 6 sites. The site was established in 2003 when pennies were placed in the pan; however, usable photographs of clasts at the site were only available from the July and September 2006 visits. Selected clasts ranged in size from approximately 1 cm to over 5 cm (Appendix U). The colors of the selected clasts included hues of green, beige, and white. Little change in the position of the selected clasts occurred between the two month period (Table 23, Figure 74).

Table 23. Summary of clast data, Site B, DMN.

Variable	Number of clasts*
Number located	15
Number buried	0
Number rotated	0
Number overturned	0
Number moved laterally	0

*Data summarized from Appendix V

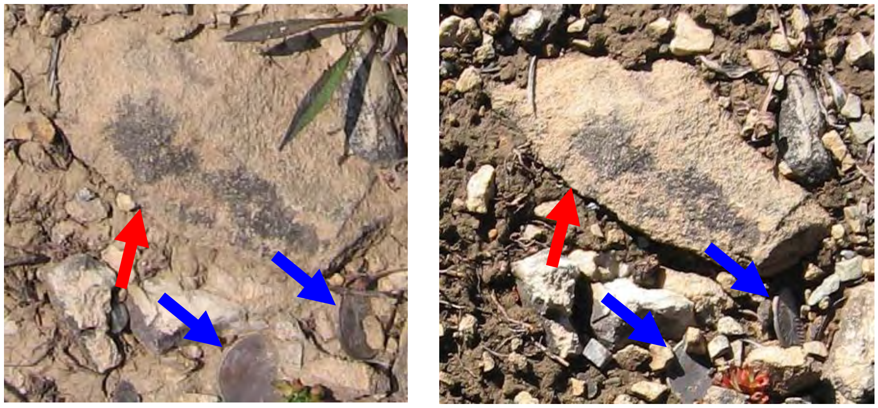


Figure 74. Clast 10, Site B, DMN, July 2006 (L) & September 2006 (R).
Red arrows point to clast 10. Blue arrows indicate pennies.

The only recorded change between the visits was the removal of sediment from four clasts (numbers 2, 4, 8, and 10), or the “unburying” of the clasts. These clasts ranged from size from approximately 1 cm to several cm in length.

Site I, SP. Photographed since August 2005

The 15 clasts selected for observation at Site I ranged in size from approximately 1 cm to 4 cm (Appendix W). The colors of the selected clasts were in hues of green, brown, and grey. Changes in clast positions were observed between 2005 and 2006 (Table 24). One clast (number 3) was not located in 2006. Comparisons between the 2005

Table 24. Summary of clast data, Site I, SP.

Variable	Number of clasts*
Number located	14
Number buried	5
Number rotated	12 clasts (mean of 58°)
Number overturned	9
Number moved laterally	11 clasts (mean of 3 cm)

*Data summarized from Appendix X

and 2006 photographs (Figure 75, clast 3 indicated by red arrow on left photo) illustrate movement occurred with other clasts in the same area of clast 3. In 2005, the area around clast 3 contained several clasts larger than 2 cm. One clast (yellow arrow) rotated between 2005 and 2006 and moved approximately 2 cm towards north (on the photo). An oblong-shaped clast (green arrow) moved west (on the photo) over 1 cm. A clast (blue arrow), approximately the same size at clast 3, moved under 2 cm southwest (on photo). Finally, a small white clast (less than 2 cm), moved over 4 cm (approximately) to the (photo) north to rest between large clasts.

In 2006, five of the selected clasts (numbers 4, 5, 6, 9, and 15) were found partially buried. Burial of the clasts was from other clasts rather than fine-grained sediment, as was seen in Sites A and B at DMN. Clast rotation was observed in twelve clasts, with numbers 11 and 5 not exhibiting any signs of rotation. Rotated clasts turned an average amount of 67° with rotations ranging from approximately 25° to 180°. For example, clast 1 rotated approximately 40°, as evident by the direction, in which the top part of the clast is pointing. Seven clasts (numbers 1, 2, 4, 7, 8, 12, and 15) rotated to the right to arrive at their 2006 positions, with one clast (number 10) rotating either right or left 180° (Figure 77) to arrive at its 2006 position.

Lateral movement across the pan's surface was evident in eleven clasts. The clasts moved an average of 2.7 cm between site visits. The movement amount was probably overestimated since the diameter of a nearby penny on a photograph was used to calculate distance, and the penny's actually diameter may have been slightly distorted by oblique photography. Eleven clasts moved laterally from their 2005 positions. For instance, by 2006, clast 1 had moved up and to the right of its 2005 position an estimated

3.8 cm (Figure 76), whereas another rock (blue arrow on Figure 76) moved in the opposite position (down and to the left). Four clasts (numbers 8, 10, 12, and 13) moved over 5 cm. The pennies nearest each of three clasts moved 1 (number 13), 1.9 (number 10), and 3.9 cm (number 12). Clasts 8 moved the greatest distance at approximately 8 cm (penny 8 was not found).

Ten clasts (numbers 5, 6, 7, 8, 9, 10, 11, 12, and 15) overturned so that another edge or side of the rock was showing. For instance, clast 10 was located above penny 10 and had a flat surface showing in 2005 (Figure 77). In 2006, the clast was found below penny 10 and had overturned to expose a rounded surface.

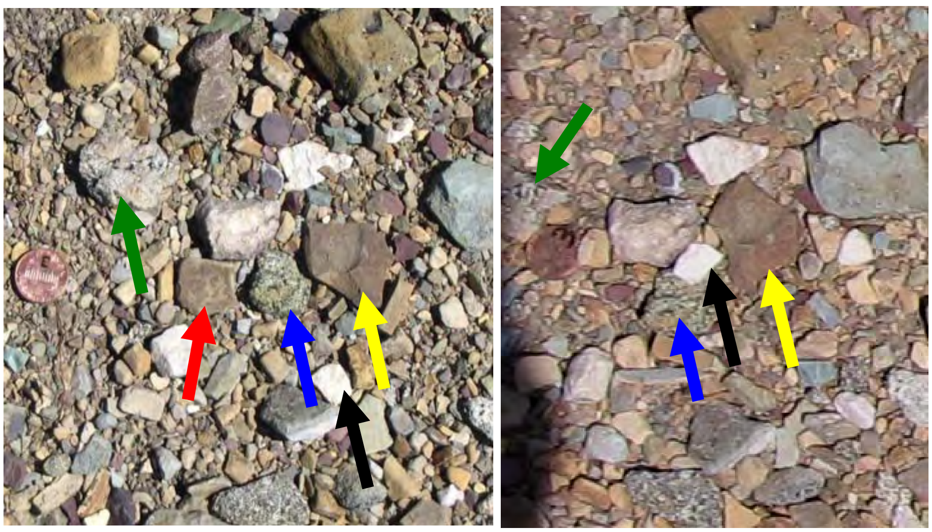


Figure 75. Clast 3 (arrow), Site I, SP, 2005 (L) & 2006 (R, not found).
Colored arrows correspond to the same rock in both photos.

Figure 76. Clast 1 (arrow), Site I, SP, 2005 (L) & 2006 (R).
Blue arrow indicates another clast mentioned in text.

Figure 77. Clast 10 (arrow), Site I, SP, 2005 (L) & 2006 (R).

Nail heaving

Divide Mountain

Nails at Divide Mountain were placed in pans in July 2006. Approximately 2 months later (65 to 75 days from the time of placement), the sites were revisited. At all sites, multiple nails were observed at elevated heights above the ground (Table 25) (see Figures 24-27). Visual inspection of the pan during the site visits concluded that the depth of the pans did not change between July and September 2006. Because the depth of

Table 25. Results from nail heaving at Divide Mountain.

Site	Number of nails at each site	Maximum amount of heaving, mm	Number of nails heaved (%)
DMS			
4 (Rocky)	15	3	3 (20)
5 (Deranged)	20	8	13 (65)
6 (Lambchop)	15	5	9 (60)
DMN			
C (Little Lip)	10	6	6 (60)
D (No Lip)	10	4	5 (50)

the pans did not increase over the two month period, the difference in the nail height between July and September is attributed to heaving, likely frost-related. Because of clasts surrounding the nails, particularly at the DMN sites, individual heaving amounts of nails were not collected, but rather the maximum amount of heaving occurring at each site.

The maximum heights of heaved nails at DMS ranged between 3 and 8 mm. The fewest number of nails were heaved at Site 4. This site also had nails with the lowest maximum heaving height (3 mm). Site 5, also at DMS, contained nails heaving up to 8 mm, and was the site containing the most nails that heaved a millimeter or more above the surrounding surface (65% of 20 nails). Approximately half (52%) of the nails at DMS did not exhibit any type of movement or heaving. For example, Figure 78 contains a set of photographic pairs of a nail at the initial placement (July 2006) and when the site was revisited (September 2006). The nail was placed into the miniature centers of fine-grained sediment. In September, the nail head was still resting on the surface. Small gravel had appeared but the fine sediment was still present.

Figure 79 consists of nails from two sites at DMS and illustrates the extent and angle of seasonal heaving occurring at the sites. In the right photograph, two nails are seen; with the one in the foreground having been heaved a few millimeters from the ground, whereas the nail in the background does not exhibit any evidence of having been heaved. The left photograph shows a nail exhibiting a high amount of seasonal heaving of over 1 cm at Divide Mountain.

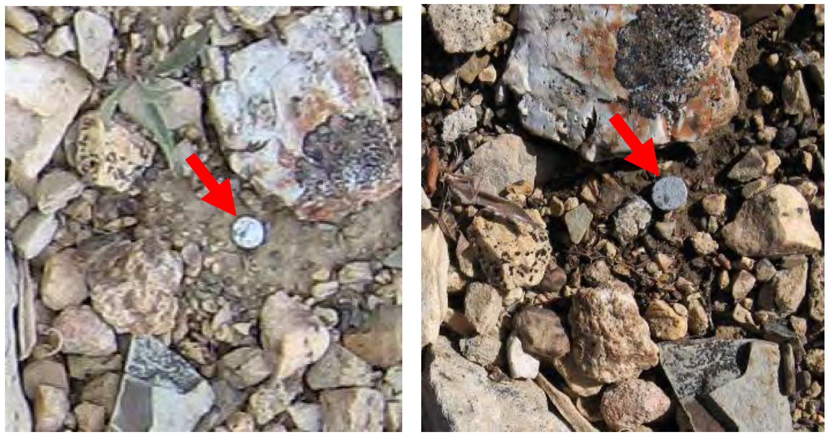


Figure 78. Nail at Site 5, DMS, July (L) & September 2006 (R).

Figure 79. Nail examples at DMS, Sites 4 & 6, September 2006.
Two nails visible in right photo (one heaved and one not heaved).

Eleven of the twenty nails at the DMN sites had been heaved above the surface when the site was revisited in September 2006. Site C had more heaved nails (6) and a higher maximum heaving (6 mm) than Site D (maximum heaving of 4 mm with 5 nails). For example, Figure 80 collectively shows three nails at Site C, two of which have been heaved. The third nail, located in the upper portion of the right photograph, still has its nail head flat on the surface. Figure 80 also shows nails being heaved in between clasts. Unlike the sites at DMS where small gravel and fine sediment dominated the pan with clasts interspersed throughout the pan, the surface of Sites C and D on the north side of the ridge consisted of a mixture of clasts and fine-grained sediment, with some small gravel. Therefore, nails were placed in spaces between the clasts and on the edges of the pans. As shown in Figure 81, the clasts shifted between the time the photographs were taken, but little other change occurred. The clasts did not prevent the nails from heaving as none of the nails were buried or covered by clasts. Additionally, nails placed in areas of the pans dominated by fine sediment did not show a propensity to be heaved more than those nails interspersed with clasts.

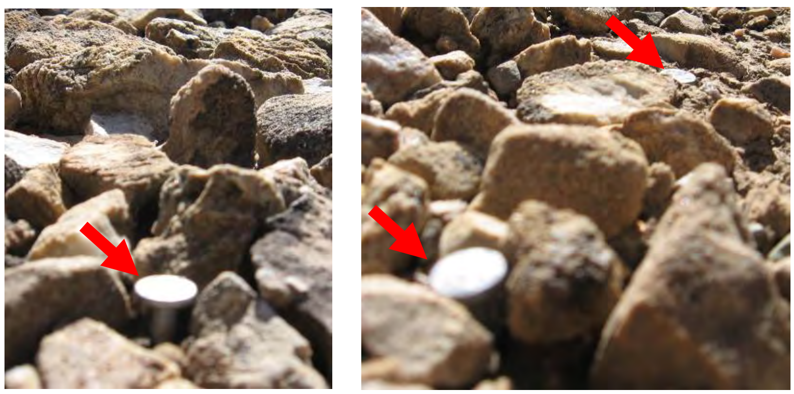


Figure 80. Nail examples at Sites C, DMN, September 2006.
Two nails visible in right photo (one heaved and one still flat).

Figure 81. Nail at Site C, DMN, July (L) & September (R), 2006.

Siyeh Pass

The mean annual amount of heave of nails at Site I was 5.9 mm, with a maximum heaving amount of 14 mm (Table 26). Individual heaving rates are presented in Table 11.

Table 26. Results of individual nail heaving at Site I, SP.

Nail	Heaved (mm)	Nail	Heaved (mm)
1	8	6	2
2	5	7	0
3	7	8	2
4	14	9	9
5	11	10	1

Nails were assigned numbers for ease of the discussion of the results. One nail (number 7) did not show any evidence of heaving and the nail head was covered with small gravel when the site was revisited in July 2006. All other nails were clearly visible and free of sediment. Three other nails (numbers 6, 8, and 10) were heaved 2 mm or less but were visibly heaved enough so that the nail head was not resting of the pan surface.

Figure 82 illustrates the spatial distribution of heaved nails. Two nails heaved over 11 mm and are shown in black on Figure 82. They are in a near-straight line of nails heaved above 5 mm.

Figure 83 is a set of photographs taken of nail 5, with the left photograph illustrating the position of the nail and surrounding gravel and clasts at the time of initial placement (July 2005). The right and bottom photographs show the conditions in July 2006, showing the changes that occurred both to the nail and the surrounding material during the intervening 12 months. Nail 5 heaved 11 mm during the 12 months between site visits (the second highest heave amount at Siyeh Pass). The bottom center photograph is an oblique photograph of nail 5 illustrating amount of heave. As is shown in the photograph, the nail is at a slight down slope angle. The resultant positions of three other heaved nails at Siyeh Pass are shown in Figure 84. The left and right photographs

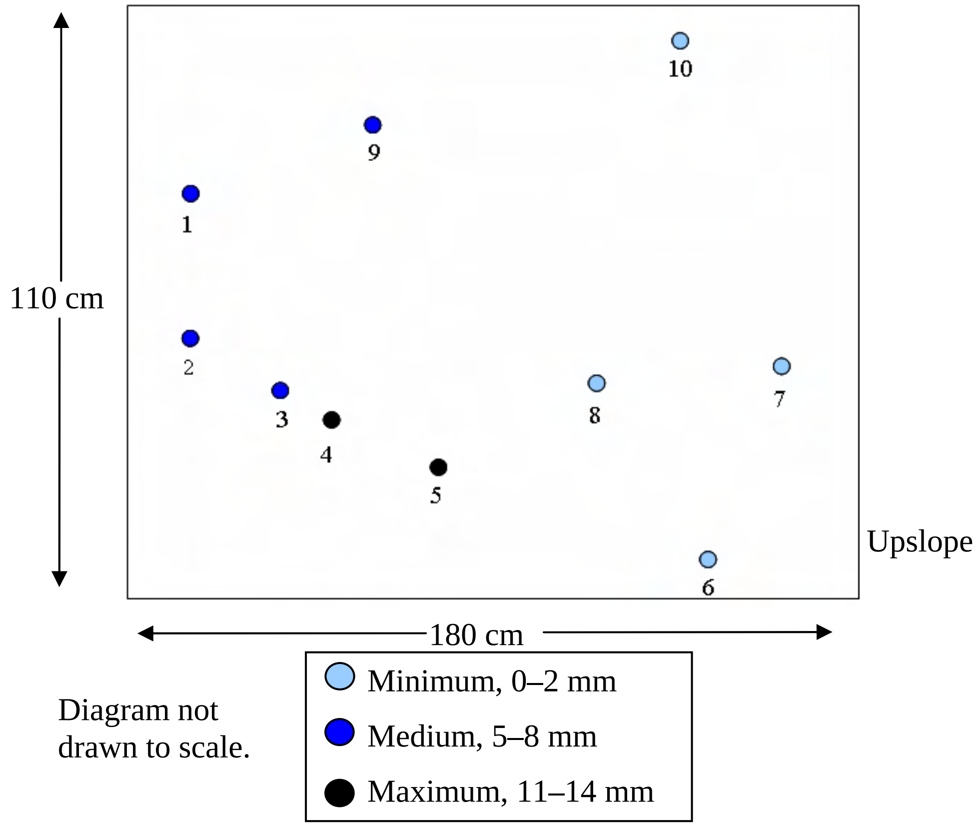


Figure 82. Diagram illustrating nail distribution and heaving, Site I, SP.

illustrate nails resting at slight angles, whereas the nail in the center photograph was heaved in an upright position.

In 2005, nail 5, in addition to nails 2, 4, and 8, were placed in small fine sediment centers surrounded by small clasts and gravel. None of the fine sediment centers were evident when the site was revisited. For example, one year later, small clasts and gravel abutted against nail 5 (Figure 83). The other nails were placed in areas containing small clasts but not necessarily well-defined centers of sediment. When re-visited, the areas surrounding these nails appear similar to those placed in fine sediment centers. For instance, a pair of photographs (Figure 85) showing nail 8 illustrates, in 2005, a small sorted gravel area into which the nail was placed. In 2006, the nail is elevated above the surface and the area is unsorted with three clasts surrounding the nail.

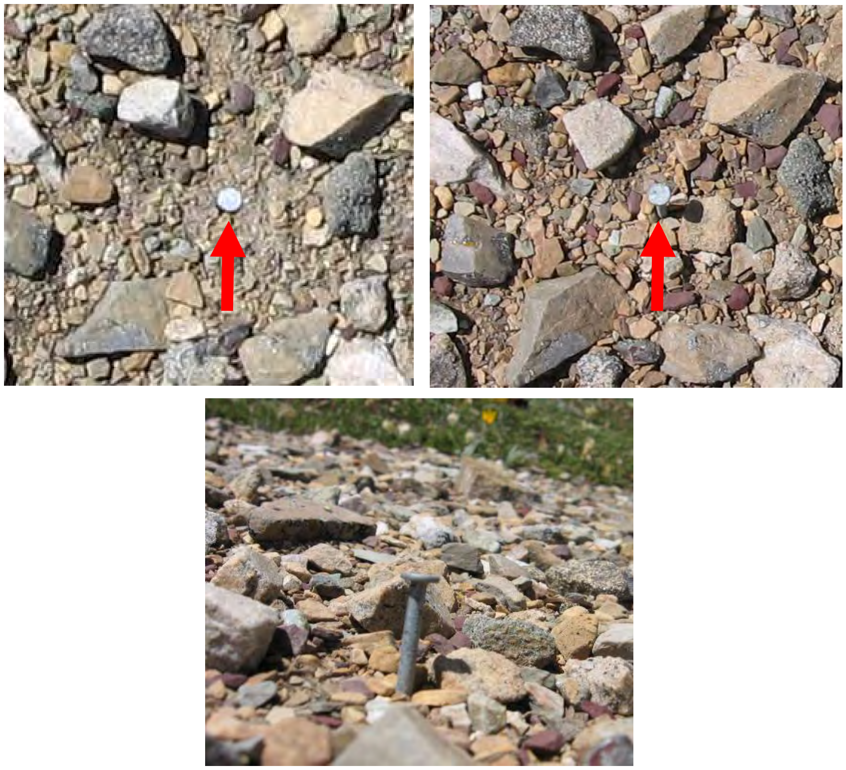


Figure 83. Nail 5, Site I, SP, 2005 (L) & 2006 (R, and bottom).

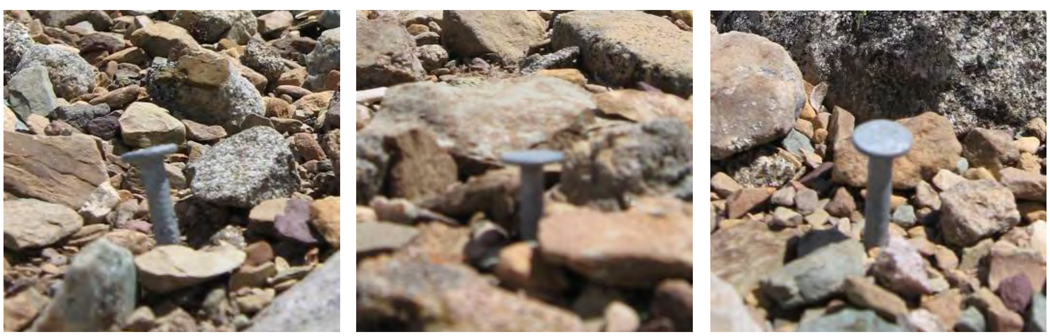


Figure 84. Examples of heaved nails, Site I, SP, 2006.

Figure 85. Nail 8, Site I, SP, 2005 (L) & 2006 (R).

CHAPTER SIX

DISCUSSION AND CONCLUSIONS

Discussion

The objective of this dissertation was to investigate the surface movement occurring in patterned ground environments in the alpine tundra region of GNP. Through observations of six sites over one to three years, the movements of clasts, markers, and nails were recorded. These sites were located in needle-ice pans and relict solifluction treads and risers. The implications and processes believed responsible for the movement of these objects are discussed in this chapter, as is the direction future research may take as a result of the work completed in this dissertation.

Four questions were answered in this dissertation. Question one was concerned with confirming surface movement at the chosen study sites. Two of the main locations (DMN and SP) contained relict treads and risers originating from a colder environment. Therefore, it was crucial to first confirm surface activity was still occurring at the sites. The main problem encountered with this question was the lapse in time needed to confirm movements. This issue slowed the project and limited the amount of data eventually collected. Question two tried to formulate a description as to the nature of movement of individual objects in pans and on turf-banked terraces. Markers were used to answer this question and four variables of penny movement were collected at each site.

Clast movement supplemented the marker data and provided additional variables related to movement. Data from this question were difficult to collect because site maps illustrating the original location of markers were not available. Additionally, markers were difficult to locate from photographs taken during the fall months because vegetation took on the same appearance as the edges of pennies when they were buried in sediment. Question three sought to describe the changes occurring on the surfaces of the sites. The method of repeat photography was used to document the changes in the surfaces; in addition, it was used to document the movement of individual clasts and markers from question two. Problems with this method included camera malfunction, inconsistent coverage in each pan, and poor resolution of some photographs. Question four sought to bridge the data collected from questions two and three and pair them with possible processes operating at the sites. Specifically, changes in nail heights above the surface were collected at each site. The central problem with this question was the limited data available from seasonal site visits.

Confirmation of surface movement

Question one sought to confirm whether surface movement was occurring in needle-ice pans and on solifluction treads. Turf-banked terraces and the associated treads and risers were considered relict; however, movement was believed to still be occurring on the surfaces primarily because of the lack of vegetation on the surfaces and the well-defined edges. Two factors were considered in whether surface movement occurred: penny overturning and the success in relocating pennies. Surface activity was first confirmed in 2004, after Sites 1, 3, and B were re-visited for the first time and pennies had overturned at all three sites. None of the relocated pennies had overturned at Site B (Big Lip) one year after movement (in 2005); however, only seven pennies of the original 15 were found.

At DMS, the success of relocating the markers decreased as time passed from when the markers were first placed, suggesting that the markers were becoming increasing entrained with clasts and fine-grained sediment the longer they were left in the pan. Additionally, more pennies were lost at the DMS sites than at DMN and SP sites. After three years in place, fewer than 60 % of the pennies at Sites 1 and 2 (Hoofprint and Deranged, respectively) could be found. Pennies were disappearing at a slower rate at the third DMS site (Site 3), with only 3 pennies missing in year two whereas Sites 1 and 2 had 5 and 7 pennies missing respectively.

Surface movement occurred at different temporal scales, ranging from weeks to months. Spatially, the clasts on the surfaces of the study sites changed positions, indicating a process affecting the entire pan, not just individual clasts and markers.

Individual marker and clast movement

Question two sought to observe the temporal and spatial movement at a microscale level through the examination of individual clasts and markers. Primarily through the use of repeat photography, four variables of movement (burial, lateral movement, vertical tilt, and overturning) were recorded. The similarities and differences of the movement of these variables are discussed below, followed by a discussion on the possible processes operating on the individual objects. Two following sections contain (1) a comparison between the results of movement rates recorded in this dissertation and movement rates recorded in the literature; and (2) how the objects may have moved. A final section discusses alternative theories of movement, including raindrop splash, karst processes, and animal disturbances.

Similar clast and penny movement

Similarities between the lateral movement and burial of clasts and pennies prove that pennies can be used to observe the movement of a pan’s surface. The use of in situ clasts, neither painted or otherwise marked, provided undisturbed additional data on the individual movement occurring at each site. Overall, clast movement occurred concurrently within small areas of each pan. Additionally, clast movement on one side of the pan was not a predictor for movement in other parts of the site. However, the different results between overturning of clasts and pennies, and the unsuccessful attempt to use vertical tilt to observe clasts (a variable successfully documented in pennies) illustrate that the use of only one type of object (i.e. either pennies or clasts) is not a good choice for monitoring surface movement.

Differences between clast and penny movement

At each site, individual clasts and markers moved differently over time. Two variables which illustrated this point were overturning and burial. One variable was discarded (vertical tilt) for clast movement description and replaced with another variable (rotation). Rotation measurements were not possible for markers but were successful for clasts. The variance in the movements of markers and clasts were likely caused by 1) differences between the shapes of clasts and markers; 2) differences between clasts and markers sizes; and 3) locational differences between the objects.

First, the markers are thin, smooth, and perfectly round whereas clasts in the pans had a wide range of shapes, including clasts with similar thicknesses as the markers (e.g., clast 1 at Site B, George, DMN). Clast overturning rarely occurred. The thinness of the pennies encouraged overturning from Lincoln's Memorial to Lincoln's Profile and vice versa. As the penny was elevated, for instance, by sediment pushing one side of the penny upwards, a threshold for falling over was reached and the penny was able to fall forward without the buffer of an irregular surface. This was the probable course for the overturning witnessed in penny 7, Site 3 (Porkchop) at DMS in Figure 50.

Second, the sizes of the clasts were predicated on the clasts being large enough to been seen with the resolution of the site photographs. However, every effort was made to include a range of clast sizes similar to pennies in order to compare the movement. Clasts were rarely lost during the observation period. The size and shape of the pennies contributed to the loss of pennies at the SP and the DMS sites. A penny's size contributed to its loss because, at 19 mm, it is easily obscured by larger clasts and covered with sediment. The thin width and smooth surface of the penny made it easy to be wedged between clasts (e.g. Figure 49).

Finally, although markers and clasts in an individual pan were observed, they were not located in the same place within the individual pan. Pennies, when possible, were in fine-grained centers of miniature polygons whereas clasts were chosen in situ and obviously not located in the middle of fine-grained centers. Clasts spatially close to pennies were therefore selected for this dissertation to help mediate locational differences. This disparity in the locations of pennies and clasts meant, however, that the objects were subject to different micro-environmental conditions, including differential frost heaving.

Possible processes responsible for movement

Similarities in the movement of clasts and markers were likely the result of processes operating at each site. For instance, between site visits, both clasts and pennies at Site 1 (Hoofprint, DMS) became buried and unburied. This implies that the same processes were affecting clasts and pennies, although not necessarily at the same rate. Additionally, the same processes were not necessarily operating at every site. For instance, clasts and pennies at Site 1 (Hoofprint, DMS) rarely moved laterally across the pan (Appendix G). However, clasts and pennies at Site I (Rachel, SP) were observed to have moved laterally more in one year than pennies and clasts at Site 1 (Hoofprint) moved in 3 years of observations. Overall, clasts and pennies at Siyeh Pass moved laterally whereas pennies and clasts at Divide Mountain sites did not move substantially. This result suggests that either the site conditions at Siyeh Pass are more conducive for lateral movement and/or the processes responsible for the lateral movement were more active at Siyeh Pass than Divide Mountain.

Using the four variables as predictors towards future movement was not successful other than to record the overall movement occurring in the pans. For instance, marker burial not a precursor to a penny being lost during subsequent site visits. As an example, penny 5 at Site 1 was observed buried less than 66% in 2004 and 2005; however, the penny was not found during either of the 2006 visits. But, penny 1 was been observed as buried over 66% (but was still visible) during every site visit beginning in

2005. Pennies 6 and 9 were significantly buried when they were observed in July 2006, but were be found in September 2006.

The angle of a penny's vertical tilt was the best (but admittedly weak) predictor variable when observing the movement at Sites 1 and 2. Twelve times at Sites 1 and 2 pennies observed leaning at a 66% or more vertical angle could not be found at the subsequent visit (cf. Figure 86). A hypothesis for the relationship between vertical tilt and penny loss is that the high angle of rest created an unstable situation where a penny, thin and smooth, was able to fall between shifting clasts. This shifting and falling between clasts may be the reason why so few clasts were lost. The angular clasts were not smooth, thin, and round and could not slip between clasts.

Figure 86. Penny 10, Site 1, DMS, 2004 (L, arrow) & 2005 (R, no penny).

Implications for patterned ground rates

Minimal amounts of lateral surface penny movement were recorded throughout the study period. Movement rates at Divide Mountain were generally under 1 cm yr^{-1}. Although only data from one year's movement could be reported at Siyeh Pass, a preliminary rate of movement for Siyeh Pass has been calculated. Site I (Rachel, SP) exhibited the most movement, with three clasts moving an average of 3 cm yr^{-1}. These rates are lower than Pérez (1992a) reported in the Venezuelan Andes with movement of 60.3 cm yr^{-1}, however the rates calculated at Siyeh Pass are higher than in the White Mountains, where movement in frost boils was calculated at 1 cm for 3 years (Wilkerson 1995). GNP and the White Mountains are environmentally different, with the White Mountains at a lower latitude and high altitude; additionally, the White Mountains research was conducted in frost boils versus the GNP research occurring within needle-ice pans and turf-banked terraces. The higher rates reported by Pérez (1992b) were unsurprising compared to the data collected at Siyeh Pass and Divide Mountain as the environmental conditions of the Venezuelan Andes are more extreme with a drier environment, higher latitude, and higher altitude. Additionally, Pérez's (1992b) data were from a multi-year study, making his dataset more robust.

Explanations for surface and clast/marker movement

The existence of solifluction turf-banked terrace tread and risers and needle-ice pans signify a past or present colder periglacial environment at Siyeh Pass and Divide Mountain. The lack of vegetation in the needle-ice pans at Divide Mountain and on the treads at Siyeh Pass indicates that periglacial processes were active between 2003 and 2006 (i.e. during the time of this dissertation). Frost-related action was primarily responsible for the movement of clasts and markers at the sites. The quantity of soil water, and the duration and severity of freezing obviously affects the amount of expansion occurring; however, no data on these variables were available. Differences in the amount of movement at the study sites were possibly influenced by different amounts of soil water.

Markers and a representative selection of clasts at each site illustrated the movement that was occurring on and across the surface. The markers were observed in tilted and/or overturned positions, indicating that a process forced the penny upward and in some cases, flipped them over. In most instances, pennies in vertically tilted positions were resting between or against clasts. The positions of these pennies suggest that the clasts on the surface were forced upward, lifting one side of the penny. In some instances, the edge of the penny was tilted enough to overturn the penny. Clasts were moved in response to the expansion of the surface. Unequal expansion of the surface (i.e. differential frost heaving) created areas that moved at greater amounts than the areas among them. Marker disappearances occurred as clasts were shifted, either in response to freezing or thawing, and were buried. Repeat photography of several markers and clasts at Site 1 (Hoofprint, DMS) illustrated the progressive trend towards burial (i.e. Figure 26, Figure 27, Figure 28, and Figure 29). The area occupied by fine-grained sediment also expanded in volume as it became saturated by water and froze, entraining pennies that may have sunk into the moist sediment before freezing.

Like pennies, burial of clasts occurred during freezing or thawing. The condition of clast 5 from Site 1 (Hoofprint, DMS) will be used as an example (Figure 67). The clast was first observed partially buried in 2003. The position of the clast changed between every site visit. During thawing, when the ground is moist, the weight of the clast caused it to sink into the sediment. However, the same resultant burial would have occurred if the surrounding sediment expanded upward during freezing, but the area below clast 5 (possibly due to insulation from the clasts) froze at a slower rate or not at all. The freezing and thawing process ensures that that clasts and pennies do not follow any pattern of movement beyond the fact that movement occurs. Further inferences as to the processes cannot be made without more data. Future research regarding the processes occurring in the sites is discussed under the “Future Research” section of this chapter.

Frost action or freeze-thawing is also responsible for moving clasts and pennies between seasonally timed site visits. The position of pennies, notably in their vertical tilt, changed from when they were observed at Site 3 (Porkchop, DMS) in May 2005 and the first of August 2005. The change in the vertical tilt suggests that a process occurred that could shift clasts, causing angles to increase and decrease, during the time between site visits. During the May 2005 visit, snow was still present on Divide Mountain near the DMN sites. No snow was visible near Site 3 or the other DMS sites; however, temperatures recorded at St. Mary suggest freezing temperatures probably occurred at Divide Mountain when the adiabatic lapse rate is taken into account (NCDC 2006).

In addition to frost action, a second process, surface wash, occurred at the DMN sites. At the DMS and SP sites, the volume of clasts in each pan exceeds fine-grained sediment, but the opposite is true at Sites A (Big Lip) and B (George) at DMN. The surfaces of these sites contain mostly fine-grained sediment that, at times, gives the pan surfaces a “muddy” appearance. Pennies have been observed lying flat covered with dried sediment on their surfaces. The disappearance and subsequent re-appearance of pennies at these sites were primarily the result of surface wash. For instance, at Site B (George), penny 11 could not be found in July 2006. However, the penny was found in

September 2006 at or near the same place it was observed in 2004, suggesting that the penny was lightly covered with sediment in July 2006 (see Figure 59).

The surface wash, or sediment-laden water, was of sufficient quantity that it covered the surfaces of the pennies and clasts. This created an environment where the upper features of the pans were obscured by a fine layer of sediment (Figure 87). Water entering the pans had little energy to regularly move objects within the pan, as pennies were found in the same general area where they were initially placed. This water probably drains quickly (within hours) as standing water was never observed in either site during a site visit.

Figure 87. Penny 6, Site B, DMN, July 2006.

Alternative explanations for marker and clast movement

Over the course of the dissertation several possible alternative explanations were provided as the cause of surface and marker/clast movement. Each of the possibilities is addressed below.

First, raindrop splash was suggested as the process responsible for the movement of the pennies, specifically the overturning of pennies. This hypothesis was rejected on the basis of the observed positions of the pennies. A few pennies were observed in delicately balanced positions among clasts. The positions of these pennies indicate that they came to rest in their positions from a slow event. For instance, using the penny in Figure 88 as an example, it could not have been placed in this position by a raindrop. The penny, when it reached this precarious position by a raindrop, would have continued to roll on its edge, until it dissipated the energy created by the raindrop. Additionally, this hypothesis does not account for clasts, several times the size of pennies, being moved and overturning. A slow movement of clast being lifted due to freezing would also allow for pennies to be overturned. Finally, this hypothesis does not account for pennies being found half buried by sediment at a 90° angle. The force of a raindrop could not force the penny into sediment at that angle.

Figure 88. Penny 8, Site 3, DMS, May 2005.

Second, karst topography refers to landforms created by karst processes, including sinkholes, uvalas, springs, and disappearing streams. Karst features require limestone and moisture for development. In this dissertation, questions were asked as to whether springs and/or groundwater were affecting the movement of the study sites. Precambrian limestone is present at both Divide Mountain and Siyeh Pass; however, the climates of the sites are dry. None of the six pans were moist in the summer, nor was the surface of Site 3 (Porkchop, DMS) wet in May 2005. The pans at the Divide Mountain sites were partially moist in September 2006. In September, 2005, Site A (Big Lip) was barely moist and in October 2005 the same site was again moist with half of the pan snow covered. Streams traveling through the sites (both at Divide Mountain and at SP) were never observed, nor were any springs, or any overly green patches of grass that could be indicative of the presence of a spring. Therefore, I reject any connection between surface movement and karstic features.

Another suggestion was that animals were responsible for markers disappearing from the pans. The natural shine of the pennies has been suggested as a lure for rodents to take them. The Wood Rat (*Neotoma cineras*), also known as a packrat, is especially known for fostering shiny objects and is found in GNP. Because no attempt has yet been made to locate the pennies buried in the pans (see the section on future research), the exact cause of the loss has yet to be determined. However, several points lead me to reject this possible explanation. First, at each site, pennies were found in all stages of burial, by clasts and fine-grained sediment throughout the observation period. They were not found on the surface but were being actively buried, suggesting that the lost pennies were instead buried. In one instance, only the edge of the penny could be viewed between large clasts (Figure 30, penny 6, Site 1, Hoofprint) and was not found during the next site visit. Second, previously lost pennies re-appeared, suggesting again that the pennies were not taken but instead temporarily buried by clasts or fine-grained sediment. For example, a penny not seen since 2003 was found in July 2006 (Figure 22, penny 3, Site 1) and again in September 2006. In another instance, at Site A (Big Lip), in August 2005 (one year after they were placed) only 7 pennies could be located but by July 2006, all fifteen were found *at or near* their original position. Although wood rats are known for taking objects, they are not known to return them (and to their original location). Third, no evidence (i.e. sightings, paw prints, etc.) of wood rats, or other rodents, have been seen at Divide Mountain or Siyeh Pass during the visits to either place. Finally, animals become conditioned to return to places where they have found food, water, etc. If wood rats had taken some pennies, why have more pennies not been lost? And, if they were taken, why are pennies, which were, at one time, partially buried, become missing when pennies sitting on the surface of pans (cf. Figure 50) were left alone? In summary, I am unable to accept that the pennies were taken by wood rats or any other rodent.

Site changes

Question three asked whether the study sites changed in their surface appearance over time. The appearances of the sites changed slowly over the course of months, rather than the weeks Grab (1997) reported it took for miniature sorted circles to re-form in southern Africa. Although the sites were not visited as frequently as Grab visited his sites, sequentially ordered photographs of the sites show a slow change occurring. Clasts and fine-grained sediment were found in approximately the same vicinity as they were observed during previous site visits. The changes in each site's appearance were steady and noticeable (cf. Figure 32, Figure 33, Figure 34, Figure 35, and Figure 36, photos showing Site 2, Deranged, at DMS from 2003 to September 2006). Three areas of discussion about the changes in the sites are 1) site comparisons; 2) patterned ground formation and maintenance; and 3) implications for patterned ground processes.

Site comparisons

Comparisons of the sites reveal that the pans at each of the three primary sites (i.e. SP, DMN, and DMS) acted similarly in terms of movement occurring, but the main sites were distinctly different from each other. In other words, the main sites followed the First Law of Geography, which in part states that “near things are more related than distant things” (Tobler 1970, pg. 236). The sites at DMS (1, 2, and 3) showed active, but minimal, lateral movement of clasts and pennies. Site I (Rachel, SP) also showed lateral movement of pennies and clasts. Miniature sorted circles, in some form of development, were observed at Sites 1, 2, 3, and I. These sites were similar in the distribution of clasts, gravel, and fine-grained sediment. Additionally, once pennies were lost at the DMS sites, they were rarely found during subsequent visits. The gradual loss of pennies at the DMS sites is expected to continue over time, leading to the eventual loss of all pennies. This was not the case at the DMN sites, where pennies were regularly lost and found, especially at Site A (Big Lip), where only eight pennies were found in August 2005 but one year later, all pennies were found. As explained above, the DMN sites were believed to be experiencing frost action and surface wash. The above similarities and differences suggest that similar processes of formation, maintenance, or both, may have been operating at the DMS and SP sites, whereas DMN also has the additional process of surface wash to be considered. Additional data are needed before a hypothesis about possible connections between lateral movement, lost pennies, and miniature sorted circles are made.

Over the course of this dissertation, Site A or B (DMN) did not exhibit any clast sorting to suggest that over time miniature sorted circles might appear, as had occurred at

DMS. Some vegetation (which occupied <5% of the pan's surface) was located inside each pan. Directly above Site A (Big Lip) were the pans containing nails on DMN (Sites C and D, Figure 13 and Figure 14, respectively). These sites also did not exhibit any sign of clast sorting. Additionally, unlike the sites at DMS and SP, clasts at the DMN sites are relatively stable and moved little over time. This lack of movement may have been a result of the relationship between fine-grained sediment and clasts within each pan. The relationship was best observed during the September and October site visits. At those times, the soil at Sites A and B contained noticeably more moisture than the DMS sites (as evident by the appearance of the fine-grained sediment in the pans). During site visits, distinct edges, or cracks in the sediment, occasionally developed across in the surfaces at Sites A and B. These edges are best described as boundaries between moist and dry portions of the pan. The moist side also appeared to be slightly elevated when compared to the dry portion. During the September 2005 visit, Site A (Big Lip, DMN) contained several cracks, with each crack serving as a boundary between slightly elevated sediment. This is particularly noticeable along the lower edge of the photograph in Figure 89 between the crack and pan edge. Also, during these visits, the sediment appeared to encase clasts, suggesting that either the sediment had swelled or that clasts sunk into moist sediment. Cracks and swelling were not visible at the DMS sites, even though the sites were also moist during September and October visits. Site I (SP) did not contain moisture when it was visited in July 2006.

The appearance of the clasts in the fine-grained sediment could also be due to frost heaving. As described by Washburn (1973, pg. 83), the "gaps around stones" were

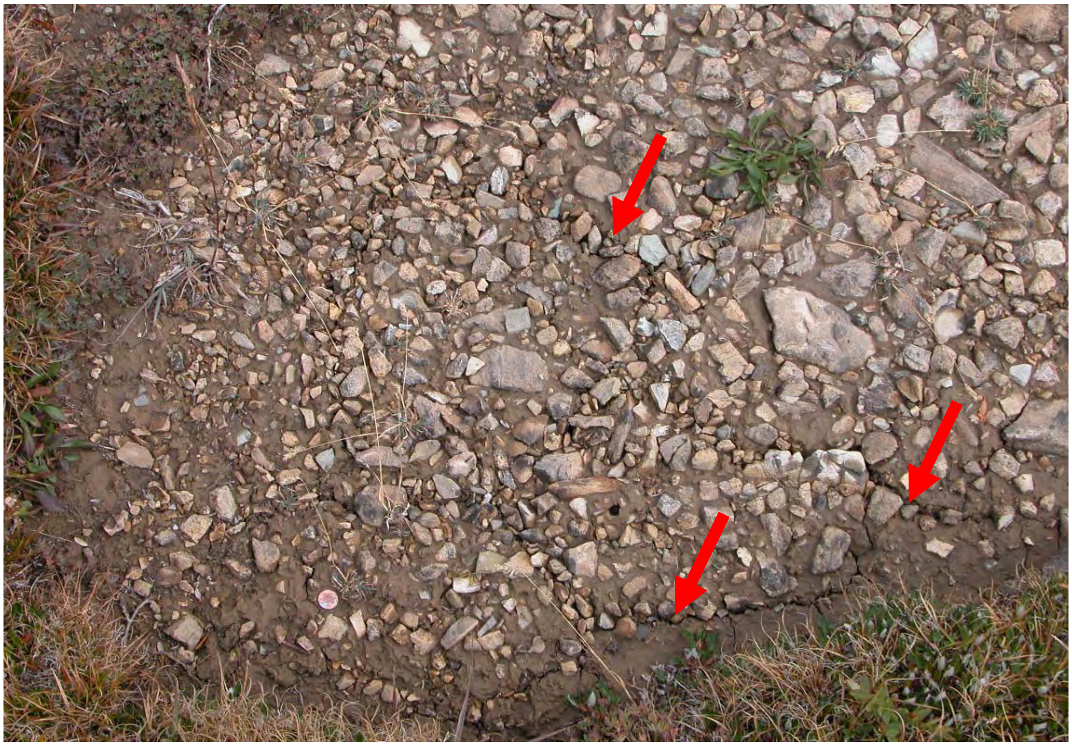


Figure 89. Site A (Big Lip), DMN, September 2005 with cracks (arrows).

attributed to frost heaving (specifically, needle-ice) under the sediment. The large clasts were left in place because the force of the needle ice could overcome the size of the clast.

Another explanation for the cracks and swelling of the fine-grained sediment is the presence of clay at the DMN pans. However, clay not only swells in response to the influx of moisture, it also shrinks upon drying, leaving cracks when dry in response to the shrinkage of the ground. During visits when the pans were dry, cracks indicative of shrinkage were not observed at either site. Therefore, another process or property of the soil likely caused the cracks and swelling. The cracks likely appeared as different parts of the pans swelled at different rates, partially due to or instigated by, the influx of water into the pan. Given the time of year the cracks and swelling were observed, diurnal freeze-thawing may also have been the source in the change of the pans. Nightly freezing temperatures were probable during the time of the observations. Differential frost heaving and needle ice have both been attributed to preferentially lifting one surface at a different rate than the adjacent surface. Further discussion of the occurrence of differential frost heaving and needle ice is located under the “Heaving” section.

Patterned ground formation and maintenance

Miniature sorted circles were observed at Sites 1, 2, and 3 (DMS). The circles were well-developed at Site 1 (Hoofprint) in 2003 when pennies were placed in the pan. In 2004, these circles had begun to break down. However, the age of the circles and the time it took them to develop is unknown. In 2006, circle reformation was observed in Site 1, although the circles were not fully developed. Therefore, the cycle of circle formation and breakdown occurred over a minimum of 5 years at Site 1. Five years was calculated based on the observation that is took more than one year for the circles to re-form and the circle disintegration occurred for at least 2 years (2004 and 2005). Reformation time would be shortened or lengthened if the environmental conditions driving the movement changed. It is important to note that the Site 1 pan did not completely become nonsorted with gravel, clasts, and fine-grained sediment interspersed, but rather the sorting was less distinct. The gutter separating the sorted circles was still in place from 2003 through 2006. The variables or process needed for circles to form at Site 1 are unknown; however, circles did not form at Site 3, located a short distance away from Site 1. Therefore, specific variables or processes were present at Site 1. As the circles were reforming in 2006, the variables needed for the cycle to continue were still present.

At Site 2, established in 2003, sorting also became less distinctive over time. However, the breakdown of the circles was more rapid than at Site 1, occurring in one year (between the 2003 and 2004 site visits). Additionally, no evidence of reformation was evident during any subsequent site visit. In September 2006, the area formerly occupied by sorted circles appeared to be completely nonsorted. Circle development at Site 2 may have been slower than at Site 1, requiring several years to reform and breakdown. The length of time the circles existed before 2003 is unknown, and the circles may have been present for several years before the study commenced. This suggests a multi-year cycle of circle reformation. However, the speed of the circle breakdown does not match with a multi-year process of circle reformation. If, however, the circles observed in 2003 were already in the breakdown stage, then the cycle of reformation is a minimum of 6 years. If the circles do not re-develop over the next several years, then the processes responsible for sorting at this site have changed, either in response to a change in the environmental condition present at the site or because a disturbance disrupted the cycle. Environmental conditions that could have affected the movement and sorting at Site 2 include moisture, temperature, and insolation rates.

Nonsorted polygons at DMN and SP maintained their condition throughout the study. Although the surface of Site A (Big Lip, DMN) changed in appearance, this was attributed to surface wash.

Implications for patterned ground processes

In general, processes related to frost were responsible for the surface movement of markers and clasts. However, which frost-related processes account for the formation of the miniature sorted circles observed at DMS and the cracks observed in the surface of the DMN sites during September and October visits? In the following sections, the system of movement is described as a process. Additionally, several processes are discussed that may be operating at Divide Mountain. From the nineteen patterned ground processes identified by Washburn (1980), four were possibly active at DMN and DMS. Another fifth process, convection cells (Ray *et al.* 1983; Gleason *et al.* 1986; Krantz 1990), is also possibly active at DMS. None of the above processes operate in isolation and can be active in tandem with other processes. Not enough data were available to hypothesize as to the processes active at Siyeh Pass, other than needle ice (discussed in the next section) and frost action; therefore, in the following sections, only the Divide Mountain sites are included.

System of movement

In frost processes, two events occur: freezing and thawing. Freezing of the subsurface caused the initial movement. Upon thawing, clasts were again moved to new positions. For instance, over 10 clasts were observed to have shifted between July and September 2006 (two of which are identified by arrows in Figure 90, Site 3, DMS). Because all clasts moved and adjusted in interaction with other clasts, the objects could not return to their original positions. Therefore, clasts moved in a system controlled by frost action.

The system that occurred at Divide Mountain is illustrated in Figure 91. It began with frost action, which included freezing and thawing of the ground. As a reaction to frost action, surface material moved. In response to the initial movement of clasts, the adjacent material adjusted their positions. At this point, the clasts were in new positions and their old positions were occupied by other material. This cycle of movement is a system whereby both positive and negative feedback occurs. Negative feedback is occurring as the elevation of the surface returns to its pre-frozen level from its frozen elevation. Positive feedback drives the surficial changes occurring as clasts and fine-grained sediment move both in response to freeze-thawing and in response to the movement of other clasts and fine-grained sediment (Figure 91).

Kessler and Werner (2003) described the feedbacks in a system capable of forming sorted patterned ground. In their research, Kessler and Werner formed sorted patterned ground through computer model simulations to prove that self-organization could be an overarching process operating in a periglacial environment. They sought to attribute the initial formation of different types of sorted patterned ground (i.e. circles, polygons, etc.) to a single process. The single process of self-organization consisted of several steps. These steps included instances of frost heaving, ice lens formation, and soil creep (Kessler and Werner 2003, pg. 380). The question is then asked: is there any evidence that self-organization was a driving process at the study sites in this dissertation? Kessler and Werner's research sought to identify a single process responsible for the initial formation of sorted patterned ground over a large area. In contrast, the work completed in this dissertation was the surficial observation of existing sorted and unsorted features over a small area. Not enough information is known about what is occurring in the subsurface at the study sites, nor has Kessler and Werner's model been tested or observed in a periglacial environment to confirm the accuracy of the model or variables. Frost heaving was operating at Divide Mountain. But sorted polygons were only found at two sites, Sites 1 (Hoofprint) and 2 (Deranged), at DMS, not at Site 3 (Porkchop). The self-organization shown in Kessler and Werner's (2003) model operated over a large area. Modeling of self-organized sorted patterned ground occurring within single pans is still needed to help understand the sorting processes occurring in miniature features.

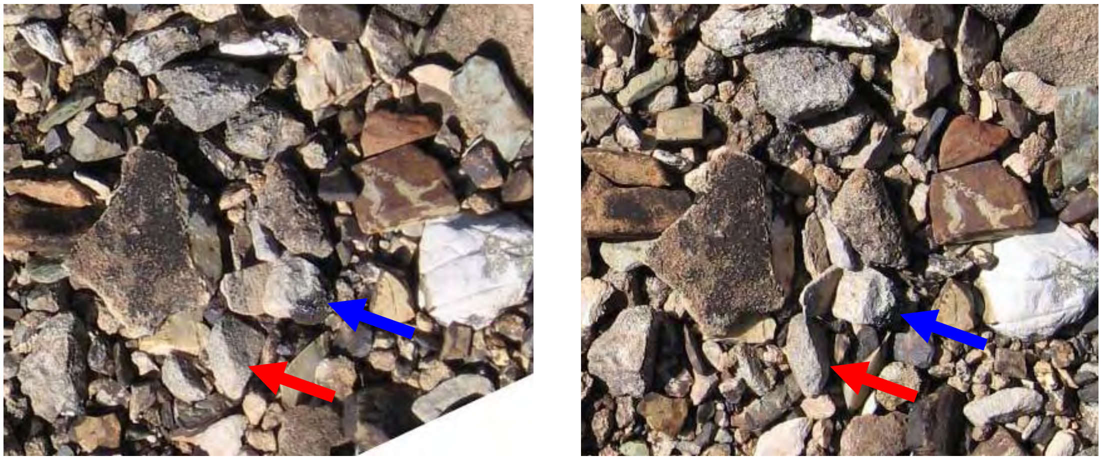


Figure 90. Clasts movement, Site 3, DMS; July 2006 (L) & September 2006 (R).

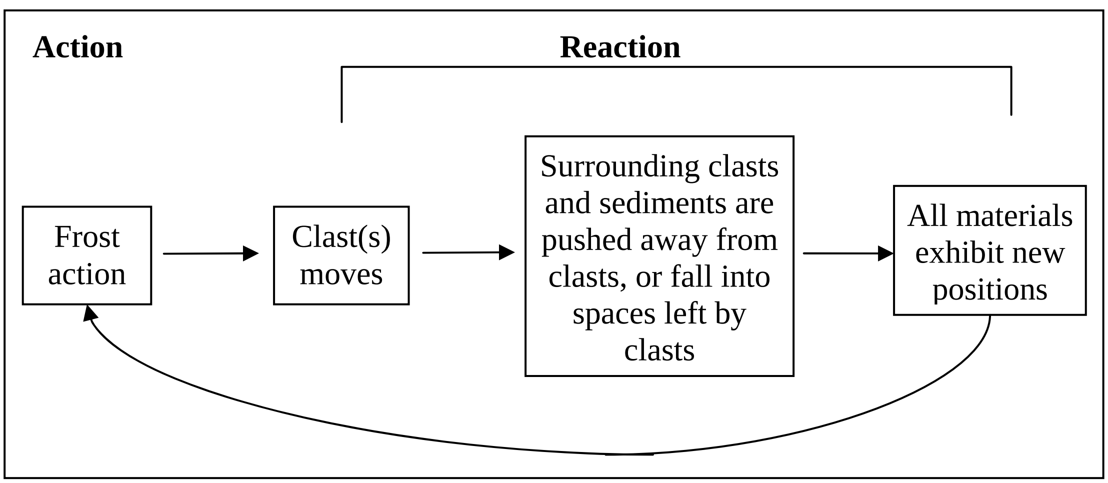


Figure 91. Diagram illustrating movement in a patterned ground environment.

Seasonal frost cracking

The first process, seasonal frost cracking, has been identified as the initiator of nonsorted polygons. Thin fissures, or cracks, develop on the surface in the fall months and disappear by the following summer (Washburn 1980). Frost cracking is difficult to detect and little is known about the criterion necessary for the process. Several features described by Washburn (1980) are similar to what was found at the DMN sites. For instance, the cracks observed at Site A (Big Lip) (i.e. Figure 89) were not visible the next year, and there was no evidence that infilling of the cracks had occurred. Vertical tilting and overturning of pennies at both DMN sites indicate some type of frost-related process is occurring (in addition to surface wash). Seasonal frost cracking would be effective at moving clasts and pennies located adjacent to, or in, cracks that form in the fall. Additionally, depending on the location of the cracks, frost cracking would explain why some pennies stayed in the same position for several seasons.

Desiccation cracking

Desiccation cracking occurs when water leaves the ground, through evaporation, drainage, or capillary movement towards ice lens' (Washburn 1980). Small cracks, or fissures, appear on the surface of the patterned ground when the soil is dry. Desiccation cracking has been attributed to multiple sizes of sorted polygons. Washburn (1980) attributed most nonsorted polygons small than 1 m diameter in size to desiccation cracking. The surface cracking associated with this process is why it is believed to be possibly operating at Divide Mountain. However, the cracks observed at DMN were present in wet, not dry, soil. Therefore, it is unlikely that desiccation cracking was responsible for the cracks observed at DMN, but other cracks may be forming during unobserved times. Further discussion or hypothesizing on the connection between sorted polygons at DMS cannot be made without further data; but, given Washburn's statement on the extensive occurrence of desiccation cracking in patterned ground environments, the process cannot be ignored as possibly occurring at Divide Mountain.

Differential frost heaving

Differential frost heaving is the uneven lifting (and falling) of a surface resulting from the freezing of soil water. An extensive discussion of the occurrence of this process at Divide Mountain is provided in the following section on "Heaving". In that section, the relation between nails and differential frost heaving is considered. In connection to patterned ground, differential frost heaving has been associated with instigating types of sorted and nonsorted patterned ground (Washburn 1980). Differential frost heaving was chosen as a possible process at Divide Mountain because of the miniature forms observed at Sites 1 (Hoofprint) and 2 (Deranged). Additionally, the difference in the movement among and between clasts and pennies indicate that the soil was moving at varying rates. The miniature frost boils observed at the DMS sites were similar in appearance to the domed centers of sediment described by Fahey (1975) in his research on nonsorted circles in the Indian Peaks region, Colorado. Fahey attributed these doomed circles to differential frost heaving. Additionally, two variables were present at both Fahey's site and the DMN sites. The patterned ground at Indian Peaks formed on treads and risers. Second, the Indian Peaks treads and risers were scoured free of snow from the wind. During an attempt to reach Divide Mountain in March 2006, the area around DMN was observed from a distance to be scoured free of snow with the areas below DMN snow-covered. An October 2005 photograph of Site A (Big Lip) illustrates how the snow is blown off of the sites and in the case of Site A, collects on one side of the pan (Figure 92). Given the similarities in appearance and site characteristics to Fahey's sites and the differences in movement rates at the Divide Mountain, it seems likely that differential frost heaving is occurring at DMN and possibly DMS.

Figure 92. Site A (Big Lip), DMN, October 2005.

Primary frost sorting

Primary frost sorting is a broadly termed process that includes freeze-thaw and needle-ice (Washburn 1980). This process is active in regions where patterned ground first develops and in areas where patterned ground was formed by another process (Washburn 1980). Freeze-thawing and needle-ice are already known to occur at Divide Mountain; therefore, primary frost sorting can be said to also be active there. However, the lack of data preclude stating whether primary frost sorting was operating first or whether another process was active when patterned ground initially formed at Divide Mountain.

<u>Convection cells</u>

The process of convection has been attributed to the formation and maintenance of sorted circles, polygons, and stripes (cf. Gleason *et al.* 1986; Hallet 1987). This process works in conjunction with frost action. The size of the subsurface convection cells are manifested on the surface as the sorted circles or other types of patterned ground. Sites 1 and 2 (Hoofprint and Deranged, respectively) are candidates for further investigation of convection cell activity being the process responsible for the appearance of the sorted circles observed at the study sites. However, convection cells generally need active (i.e. thawed) and frozen layers in the ground to operate (Gleason *et al.* 1986). The timing and depth of frozen ground at Divide Mountain is currently unknown, as is the depth of sorting when sorted circles are visible. Therefore, further speculation as to the presence of convective cells at Divide Mountain will be postponed until more data are collected.

Nail heaving

In response to question four of this dissertation, frost heaving was measured both spatially and temporally, through the use of nails. Temporal data were limited to two sets of information: nails that had heaved between a summer and fall season, and nails at a different site that had heaved at some point over a 12-month period. Spatial comparisons were limited to the study sites at Divide Mountain, which contained a 2-month set of data. At Divide Mountain and Siyeh Pass, an acknowledged problem with accurate heaving measurement of the nails was the possibility that the nails had re-settled. The resettling would cause the measurement to be lower that the actual amount the nail had heaved.

Temporal comparisons

Nails were heaved within a short time span at Divide Mountain. These visits occurred at the end of July and at the end of September, 2006. The break between site visits allowed time for possible frost-producing temperatures to occur. Maximum heaving rates at DMS were 3 mm (Site 4, Rocky), 8 mm (Site 5, Deranged), and 5 mm (Site 6, Lambchop). A disparity between heaving maximums at the DMS sites suggest that frost occurred at different scales of magnitude at each site. Given the proximity of the sites and lack of shelter adjacent to any sites, temperatures were likely similar at the sites. Wind and shadows from Divide Mountain would similarly affect the three sites. Sunlight reaches Site 5 first in the morning, but Sites 4 and 6 receive sunlight for the longest amount of time during the day because of their upland position on the slope. Consequently, the temperatures at Site 5 cooled first in the evening, possibly enabling temperatures to reach freezing for a longer time and to a deeper level in the ground. Site 5 was located the farthest down slope and was the largest of the three pans under study. Its down slope location suggests that it would have the greatest moisture availability of the three sites. Site 5 also had a more equal distribution of fine-grained sediment and clasts. Sites 4 and 6 consisted primarily of clasts with little fine-grained sediment. Therefore, the likely reason Site 5 had the most heaved nails was because of slightly greater moisture, cooler evening temperatures resulting in a longer duration of cooler temperatures, and a pan composition of clasts and fine-grained sediment.

Sites C (Little Lip) and D (No Lip) at DMN had similar maximum heaving rates (6 and 4 mm, respectively) to the DMS heaving rates. These sites are located adjacent to each other. Visually, they are different, with Site C surrounded by an edge of vegetation (hence the colloquial name of Little Lip). They have a similar composition of clasts and fine-grained sediment. Site D is located above Site C and water may drain out of Site D and into Site C. The turf-banked edge on Site C may create a micro-environment different from Site C by collecting snow within the turf-banked edge and sheltering the site from wind. Over time, because of the differences in the microenvironments of the sites, a greater range between the heaving rates at these two sites should be seen but were not within the time of this study.

Because quantitative data were not collected on individual nails, inferential statistics could not calculated on whether the DMN and DMS data samples were from the same population. However, the maximum heaving rates of nails at DMN (6 and 4 mm) fell within the maximum heaving rates of nails at DMS (3, 5, and 8 mm). Therefore, the hypothesis for future statistical testing is that data from the five sites are from the same population.

Heaving rates of nails at Site I (Rachel, SP) showed that, in addition to surface movement (as illustrated by pennies), the surface was heaving. The rates for nails left for one year were lower than heaving rates of other studies. For instance, Wilkerson (1995) recorded wooden dowels being heaved 16.8 cm in 10 months. An average diurnal heave of 10 mm was recorded by Smith (1987a), less than double the average yearly heave at Siyeh Pass. The conductivity of the metal nails could have reduced the heaving rates at Siyeh Pass and Divide Mountain. Pérez (1992b) raised questions about the use of nails in heaving studies because of concerns over the relationship between the conductivity of metal to soil freezing. Washburn (1989) reported metal and wooden dowels were heaved to different amounts. He recorded heaving rates of aluminum dowels 16 mm less than heaving rates of wooden dowels in the Canadian Arctic.

Spatial comparisons

Differences in the freezing properties of the material and the amount of soil water available throughout each site at both Divide Mountain and Siyeh Pass were the likely variables responsible for the nails being heaved above the surface. Nails were not heaved evenly to similar heights within each pan at Divide Mountain or Siyeh Pass, nor did heaving in each pan occur in a pattern. Given the unequal heaving rates at each site, with some nails showing no evidence of being heaved, differential frost heaving (cf. Fahey 1975; Van Vliet-Lamoë 1991) occurred within the DMN and DMS sites. Price's (1972) list of factors contributing to frost heaving (insolation rates, vegetation, material, and aspect) would be similar within each pan, except for the material. At the DMS sites, the number of nails that were heaved did not exceed 65% (Site 5, Deranged) and was as low as 20% at Site 4 (Rocky). At DMN, 50% and 60% of the nails were heaved. The vegetation was the same for the five Divide Mountain sites containing nails. Aspect and insolation rates were different between DMN and DMS, but the maximum heaving rates and the number of nails that were heaved at DMN were within the range found at DMS. The material was also the same at DMN and DMS; however, the distribution of the material within each pan was different, ranging from sites composed of mostly small gravel and clasts (Site 6, Lambchop), primary clasts and rocks (Site 4, Rocky), equal amounts of rock and sediment (Sites 5, Deranged), to sites consisting of more sediment than rock (Sites C and D, Little Lip and No Lip). Therefore, although no quantitative measurements were completed, the material of the sites may be the primary factor related to frost heaving at Divide Mountain.

Nails were heaved in a near-linear pattern at Site I (SP), suggesting an area of the pan was more predisposed to higher amounts of frost heave. Nails on the outer edges of Site I were heaved less than the center of the site. Unlike the sites at Divide Mountain, Site I did not have a turf-banked lip encompassing it. The site sat on a turf-banked terrace with an approximately 10-cm riser above and below the site. The length of the site is perpendicular to the slope. Differences within the material of the site were the only factor that varies throughout the site. Insolation rates, aspect, and vegetation are the same throughout the site.

Evaluation of repeat photography as a method

Repeat photography proved to be a useful technique that provided an adequate scale for recording the changes occurring at each site. Clasts, markers, and nails moved on the order of millimeters, requiring the use of high resolution imagery. At each site, vertical and oblique photographs were taken millimeters to meters above the surface. These techniques provided the required resolution for this dissertation. The use of a digital camera for the project eliminated processing costs associated with film cameras, enabling over 500 images to be collected. The quantity of images collected enabled the analysis of areas within the sites that originally were thought to be inactive. The images also provided a static record of the condition of the site for future research.

The primary issue encountered with repeat photography was the inconsistent coverage of each pan. This problem is evident from the incomplete repeat photo sets from each site (Appendix D). The problem stemmed from using a hand-held camera to collect the photographs. Ground control points were not created around each site, marking where previous photographs hade been taken. Therefore, photographs of the same area taken at two different site visits did not always match. Equipment and design solutions suggested to solve this problem include constructing a tripod to be placed over each site to take perfectly vertical images of each site. A second idea was to mount a camera on the top of a pole raised into the air in order to photograph a site in a single photograph. That idea was discarded due to problems in the logistics of carrying the equipment to the Siyeh Pass site and because strong wind gusts present at Divide Mountain would destabilize the pole. The issue of inconsistent coverage was corrected over time by taking a series of vertical photographs at the same height at each pan.

A second problem encountered using repeat photography was the resolution. Early images of the sites were taken at a low resolution and included the entire site. This factor prevented data from being collected about clasts and in some instances clasts. Later images of the sites did not have this problem. The third problem, camera malfunction, was only encountered twice. In 2004, a malfunction resulted in blurry images and a loss of data from some sites. The second camera malfunction was in 2006, when an automatic lens cover did not open completely; however, multiple images prevented any loss of data from this problem.

The data collected from repeat photography proved the method to be a greater advantage even when considering the issues encountered. In future pattered ground research, further refinement of the method is to create permanent ground control points at a site from which photographs would be taken, ensuring consistent coverage.

Future Research

The work completed in this dissertation will segue into five avenues of research. The planned future research seeks to strengthen the existing data set and knowledge learned from this dissertation by investigating the questions discovered and problems highlighted by this work. The research described in this section does not encompass all the research questions or problems raised in this project, but they do address some of the most pressing issues.

First, the existing data set will be increased by continued recording of markers, clasts, and nails observations at Divide Mountain and Siyeh Pass through 2010. Data are to be collected from Site II at SP beginning in 2007. Data from two sites established in 2006 containing markers and nails at SP will also be collected beginning in 2007 (Appendix A). Observations from these three new sites, in addition to Site 1, will quadruple the dataset at SP, allowing inferential statistical testing of data among the four sites. Additionally, calculation of annual rates of heaving of nails at DMS and DMN will begin in 2007, allowing comparison of heave rates between SP, DMN, and DMS. The diagrams of penny movement and locations will also be used to assist in the location of the pennies at future site visits.

Second, the number of clasts observed will be increased to thirty clasts at each site. Fifteen clasts were originally chosen at each site to equal the number of penny markers also placed in the site. However, the number was inadequate to encompass the range of clast sizes at each pan. Additionally, material (i.e. gravel and clasts) smaller than 2 cm (the approximate size of a penny) needs to be incorporated into the data set to determine if pennies are moving inordinately compared to the natural material in the pan because of their size or shape.

Third, at the end of the study, portions of each pan will be excavated, by layer, to observe the sorting occurring immediately below the surface and in an attempt to recover pennies that were lost during the study. The pennies' depth, recovery location (relative to their last known surface position), and vertical tilt will be recorded for comparison between lost pennies and their possible connection to the processes occurring in the pans. Excavations will continue until the depth is reached where sorting ends. The result will be observations of the subsurface movement occurring, to be compared to what was observed on the surface of the pan. Small trenches will also by dug along edges of the pans to determine the depth of sorting and lateral extent of sorting under vegetation. During the excavations, observations will be collected in connection to the patterned ground processes responsible for the movement occurring in the pans (i.e. convection cells).

Fourth, needle ice is believed to be the primary process instigating movement in the pans at DMS. Needle ice was observed in pans on DMS (but not in the study sites) in November 2003 (Butler *et al.* 2004) but was not observed during May 2005 or October 2005 visits. The extent and temporal occurrence of needle ice at DMS needs to be measured to accurately assess the impact needle ice has on surface movement. Temperature and moisture recording instruments are to be placed into subsurface at regular depths to measure when the conditions are suitable for needle ice to form, given previous research (Price 1972; Washburn 1980; Grab 2004) on the environmental conditions needed for needle ice growth. Additionally, further visits to DMS are needed in the spring and fall seasons to record needle ice lengths and spatial distribution. The conditions of the markers during visits to the DMN sites indicate surface wash is occurring to some extent. However, Site A (Big Lip) has the appearance of a needle-ice pan. Moisture and temperature recording instruments need to also be placed in pans at DMN to record the environmental conditions. Additional site visits are also needed in an attempt to observe needle ice filaments at DMN. Subsurface recording instruments will also be placed at SP; however, it is less clear whether needle ice is occurring there. The remoteness of the site makes it difficult to collect seasonal data. Data from the instruments will provide information about the environmental conditions of the sites. Data collected from the instruments at DMN, DMS, and SP will be compared and analyzed for connections to the movement occurring on the surface, and for comparative analyses among the sites.

Finally, results from this dissertation will be used to compare the patterned ground processes and movement rates in the western US mountains, particurlary Wyoming, Utah, and Idaho. Environmental conditions for patterned ground are present in the Grand Tetons and Wind River Range in Wyoming, the Wasatch, Bear River, and Uinta Ranges of Wyoming, and the Sawtooth Mountains of Idaho. However, published studies detailing the extent and rates of movement of patterned ground in these regions have not been completed. The significance of patterned ground in these regions can only be determined by comparing them to other sites. Patterned ground studies reporting movement rates in and around the edge of the intermountain region include the White Mountains (Wilkerson 1995), Sangre de Cristo Mountains (Vitek 1978, 1983; Vitek and Tarquin 1984), and in the Canadian Rocky Mountains (Smith 1987a). The results from this dissertation and the data collected through 2010 will provide movement rates from the northern portion to get a holistic picture of patterned ground activity in the intermountain west.

Conclusions

The periglacial environment that exists in GNP is not static nor is it uniform in landform type, but rather it is diverse and active with sorted and nonsorted patterned ground evident in the alpine tundra. The sorted and nonsorted patterned ground present indicates that several processes, rather than a single process, are operating at the study sites. Further evidence supporting the hypothesis that multiple processes are at work is the differences in types and rates of movement observed at the study sites. Through the research conducted in this dissertation, it is possible to narrow the list of 20 processes (Washburn's 19 processes plus convection) operative in periglacial environments in GNP to five processes. This new concise list allows future studies to focus on variables and environmental conditions associated with those five processes to further narrow the list to the actual dominant driving forces behind the movement at the study sites.

Predicting the type of movement that will occur at each of the three main study sites is now possible based on the results from this dissertation. Similar movements of markers and clasts were recorded within the sites at each of the three major study sites. These results, in conjunction with the initial surface appearances of pans at the major sites, provide enough information to understand how movement will occur in a general sense. Additionally, future research can begin with the knowledge that surface pan morphology is an indicator of the rate of activity occurring at the site. Pans with greater amounts of fine-grained sediment exposed on the surface (i.e. Sites A and B) may be experiencing surface wash in addition to frost action. Pans with miniature sorted circles shown in conjunction with the absence of vegetation (i.e. Sites 1, 2, and 3) may be assumed to be active, especially in terms of frost churning and related burial of markers. Pans located on treads without thick turf-banked edges (i.e. Site I) may experience a high degree of lateral surface movement. These predictions are important for understanding the connections between surface appearances and clast movement. Further data collection will refine these predictions and help in the construction of a model to simulate the processes operating in the pans.

Throughout the dissertation, the seasonal activity was moderate at sites already showing annual evidence of movement (i.e. DMS). At sites where movement was minimal (i.e. DMN), observations of seasonal movement was unpredictable. However, from the results of this dissertation, vertical and lateral movement can be assumed to occur within as little as 4 weeks at Divide Mountain.

The research completed in this dissertation illustrates the vertical and lateral surface movements occurring in a patterned ground environment in GNP. These movements illustrate the presence of frost-related processes. The movement is important for the surrounding environment because it creates an unstable environment that prevents tree seedlings from encroaching into the alpine tundra of the needle-ice pans and treads. The movement processes themselves may change or cease in reaction to future climate change in the area.

With the research completed in this dissertation, a connection was established between the heaving of nails and the lateral movement of markers and clasts. The processes operating to move markers and clasts were also responsible for the upward heaving of nails. Comparisons of data from the two sites reveal that the vertical heaving of nails was not equal to lateral surface movement. However, heaved nails at Site 2 had the same appearance as nails at the two nearby sites (Sites 1 and 3, Hoofprint and Porkchop, respectively).

Overall, the objective of this dissertation was to observe vertical and lateral movement of the surfaces of needle-ice pans and treads in the alpine tundra in eastern GNP. Based on the research completed in this dissertation, patterned ground is actively moving and forming at multiples sites in GNP. The objective was successfully fulfilled by recording variables indicating movement of markers, clasts, and nails. The four questions asked in this dissertation were designed to break down the objective into separate parts for specific studies. Each question was successfully answered. Preliminary base rates of lateral movement for Divide Mountain and Siyeh Pass are now known. Preliminary heaving rates for the study sites are now also known. These rates illustrate the amount of vertical surface expansion occurring at the study sites and will continue to be refined with the further recording of heaving rates. Further refinement of the rates will be accomplished over the next several seasons of fieldwork. Knowledge of these rates will aid in the future construction of a model simulating the environmental conditions present with active surface movement, and will allow an assessment of whether rates are changing in response to regional climate change in Glacier National Park.

Appendix A. Establishment dates, site visits, marker and nail information.

Site	Established	# of nails & pennies	Site Visits					
Divide Mountain North								
A Big Lip	Jul 2004	15 pennies			8-2005	9-2005	7-2006	9-2006
B George	Jul 2003	15 pennies	7-2004				7-2006	9-2006
C Little Lip	Jul 2006	10 nails						9-2006
D No Lip	Jul 2006	10 nails						9-2006
Divide Mountain South								
1 Hoof print	Jul 2003	15 pennies	7-2004		8-2005		7-2006	9-2006
2 Deranged	Jul 2003	15 pennies	7-2004		8-2005		7-2006	9-2006
3 Porkchop	Jul 2004	15 pennies		5-2005	8-2005		7-2006	9-2006
4 Rocky	Jul 2006	15 nails						9-2006
5 (also site 2)	Jul 2006	20 nails						9-2006
6 Lambchop	Jul 2006	15 nails						9-2006
Siyeh Pass								
I Rachel	Aug 2005	15 pennies 10 nails					7-2006	
II Gnomes	Aug 2005	15 pennies 10 nails						

Appendix B. List of pennies located during each visit, by site.

	Divide Mountain South												Divide Mountain North								Siyeh Pass
	Site 1 Hoofprint				Site 2 Deranged				Site 3 Porkchop				Site A Big Lip					Site B George			Site I Rachel
Site visits	04	05	06	S 06	04	05	06	S 06	M 05	05	06	S 06	05	S 05	O 05	06	S 06	04	06	S 06	06
1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	US	Y	Y	Y	Y	Y	Y
2	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	US	Y	Y	Y	Y	Y	Y
3	N	N	Y	Y	Y	N	N	N	Y	Y	Y	Y	N	Y	US	Y	Y	Y	Y	Y	Y
4	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	Y	Y	Y	Y	Y	Y
5	Y	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	US	Y	Y	Y	Y	Y	Y
6	N	N	Y	N	N	N	N	N	Y	Y	Y	Y	Y	Y	US	Y	Y	Y	Y	Y	Y
7	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	US	Y	Y	Y	Y	Y	Y
8	Y	Y	N	N	Y	*	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
9	Y	Y	Y	N	Y	*	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
10	Y	N	N	N	Y	*	N	N	Y	Y	N	N	N	N	N	Y	Y	Y	Y	Y	Y
11	N	N	N	N	Y	Y	N	N	Y	Y	Y	Y	Y	Y	US	Y	Y	Y	N	Y	Y
12	Y	Y	Y	Y	N	N	N	N	Y	Y	N	N	N	N	N	Y	Y	Y	Y	Y	Y
13	Y	Y	Y	Y	N	N	N	N	Y	Y	N	N	N	N	Y	Y	Y	Y	Y	Y	Y
14	Y	Y	N	N	Y	Y	Y	N	Y	Y	Y	Y	N	*	N	Y	Y	Y	Y	Y	Y
15	Y	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	Y	Y	Y	Y	Y	Y
Total	10	10	7	5	9	8	9	7	14	15	12	12	7	9	3	15	15	15	14	15	15

Y=Yes, penny visible; N=no, penny not visible. * indicates presence or absence could not be confirmed; however, for Site 2, field notes indicate 8 pennies were located. “US” indicates location of penny was under snow. Letter and year indicate month of visit if other than summer: “S” = September, “O”= October, and “M” = May.

Appendix C. List of repeat photography sets, by site.

Site	Complete repeat photo set	Number of photo sets
Divide Mountain South		
1 Hoofprint	60	60
2 Deranged	60	39
3 Porkchop	60	56
Divide Mountain North		
A Big Lip	60	40
B George	30	15
Siyeh Pass		
I Rachel	15	15

Photo sets were considered complete if photographs of pennies were available for each viable site visit.

Appendix D. List of dates, by site and penny, of incomplete sets of photographs.

Penny ID	Dates
Site 2 (Deranged)	
8	2003, 2005
9	2005
10	2005, 2006
11	Fall 2006
12	2004, Fall 2006
13	2005, 2006, Fall 2006
14	Fall 2006
15	2003
Site 3 (Porkchop)	
10	2006
12 and 13	Fall 2006
Site A (Big Lip)	
1-4, 6, 11, and 13	2005
12	2005; September 2005
14	2005; September 2005
Site B (George)	
5	2004 *

Unless otherwise noted, dates are for summer visits. *For Site B, photographic images were severely distorted and blurred, making comparison unusable for most pennies at this site. However some, if minimal, data were collected from images of all the pennies except the one listed.

Appendix E. Field notes (verbatim) detailing observations from Summer 2004.

Site 1 (Hoofprint)	Site 2 (Deranged)	Site B (George)
1. Tipped into crack in fines, stone on it	1. Lincoln up flat	1. Lincoln up on lower edge
2. Tipped into small stones, Lincoln on top	2. Spun 180° flat	2. Turn 90°
3. Lincoln up, ½ covered by stones	3. Lincoln up, titled 20°	3. Turn 90° other way
4. Tipped 45°, ½ covered	4. No change (very edge of pan on very fine sediment)	4. Lincoln
5. Rotated 90°	5. Tilted on edge, ½ buried in fine sediment	5. Lincoln
6. Vertical in small stones	6. Lincoln up, nestled in small stones	6. Turn 45°
7. Vertical, w/other stones also tipped vertically	7. No data	7. Turn 45°, cemented in
8. ¾ buried, by largest stone (2-4 cm) and smaller stones	8. Turned 45°	8. Turn 90°
9. Turned 160°, tipped 45°, buried under hardened fines and tiny stones	9. On edge, held by 2 cm clasts	9. Same [as when placed]
10. Completely buried, tipped 80° w/only 1-2 mm showing	10. No change	10. Turn 90°
11. Turned 120°, ½ buried, tipped 45°	11. Lincoln up, tilt 30°	11. Tip 45°, ¼ buried in crack in fine sediment
	12. Lincoln up, tilt 60°, ½ buried	12. Turn 135°
		13. Lincoln, rock on edge
		14. Turn 45°
		15. Lincoln

Appendix F. Key for raw penny and clast data.

Variable	**Categories**			
Burial	0= no burial	1=0-33 %	2=33-66%	3= 66%+
Overturn	0=Lincoln’s Memorial		1=Lincoln’s Profile	
Lateral	0=no lateral movement from *last* observation		1=lateral movement from *last* observation	
Vertical	0=minimal	1= 5 - 30°	2= 30 - 60°	3= 60-90°
Rotation	Numerical, from 0° - 360°			
“n/a” = penny vertically tilted more than 60°, determining the side the penny showing impossible.				
* = lack of previous data makes determination not possible.				
“covered”= penny or clast had overlaying clasts or sediment; and therefore, data could not be obtained from the photo.				
“PI” = poor quality photograph, indicating data could not be obtained from the photo.				

Appendix G. Penny data from Site 1, DMS.

ID	Variable	7-2004	8-2005	7-2006	9-2006
1	burial	2	3	3	3
	lateral	1	0	0	0
	overturn	1	1	1	1
	vertical	2	2	2	2
2	burial lateral overturn vertical	not found	not found	not found	not found
3	burial	not found	not found	0	0
	lateral			1	0
	overturn			1	1
	vertical			3	1
4	burial	not found	2	not found	not found
	lateral		1		
	overturn		n/a		
	vertical		3		
5	burial	2	1	not found	not found
	lateral	1	0		
	overturn	0	1		
	vertical	1	0		
6	burial	not found	not found	3	not found
	lateral			1	
	overturn			n/a	
	vertical			3	
7	burial	0	2	2	2
	lateral	1	0	0	0
	overturn	0	0	0	n/a
	vertical	0	0	1	3
8	burial	1	2	not found	not found
	lateral	1	0		
	overturn	n/a	n/a		
	vertical	3	3		
9	burial	1	3	3	not found
	lateral	1	0	0	
	overturn	n/a	n/a	n/a	
	vertical	3	3	3	

Appendix G continued

ID	Variable	7-2004	8-2005	7-2006	9-2006
10	burial	1	not found	not found	not found
	lateral	1			
	overturn	n/a			
	vertical	3			
11	burial	not found	not found	not found	not found
	lateral				
	overturn				
	vertical				
12	burial	2	2	2	3
	lateral	1	0	0	0
	overturn	PI	n/a	n/a	n/a
	vertical	2	3	3	3
13	burial	2	3	2	2
	lateral	1	1	0	0
	overturn	n/a	0	0	0
	vertical	3	2	1	2
14	burial	2	2	not found	not found
	lateral	1	0		
	overturn	1	*		
	vertical	1	1		
15	burial	3	3	not found	not found
	lateral	1	0		
	overturn	covered	n/a		
	vertical	2	3		

Appendix H. Penny data from Site 2, DMS.

ID	Variable	7-2004	8-2005	7-2006	9-2006
1	burial	0	0	2	2
	lateral	1	1	1	0
	overturn	1	1	1	1
	vertical	1	0	0	0
2	burial	0	0	3	2
	lateral	1	1	1	0
	overturn	1	1	0	0
	vertical	0	0	1	1
3	burial	2	not found	not found	not found
	lateral	0			
	overturn	n/a			
	vertical	3			
4	burial	0	1	1	2
	lateral	1	1	0	1
	overturn	1	1	1	1
	vertical	2	0	0	0
5	burial	0	1	2	2
	lateral	1	1	1	0
	overturn	0	0	0	0
	vertical	3	1	2	2
6	burial	not found	not found	not found	not found
	lateral				
	overturn				
	vertical				
7	burial	3	2	2	2
	lateral	1	1	1	0
	overturn	n/a	0	0	0
	vertical	2	2	2	3
8	burial	0	no photo	2	not found
	lateral	*		1	
	overturn	1		1	
	vertical	3		3	
9	burial	0	no photo	2	2
	lateral	1		*	0
	overturn	PI		n/a	n/a
	vertical	1		3	3

Appendix H continued

ID	Variable	7-2004	8-2005	7-2006	9-2006
10	burial	2	no photo	not found	not found
	lateral	1			
	overturn	1			
	vertical	2			
11	burial	0	1	not found	not found
	lateral	0	1		
	overturn	1	1		
	vertical	3	3		
12	burial	not found	not found	not found	not found
	lateral				
	overturn				
	vertical				
13	burial	2	not found	not found	not found
	lateral	1			
	overturn	n/a			
	vertical	3			
14	burial	0	1	1	not found
	lateral	1	1	0	
	overturn	0	1	1	
	vertical	0	2	3	
15	burial	2	1	1	2
	lateral	*	1	1	1
	overturn	n/a	0	1	1
	vertical	3	2	3	3

Appendix I. Penny data from Site 3, DMS.

ID	Variable	5-2005	8-2005	7-2006	9-2006
1	burial	1	1	3	3
	lateral	0	0	1	0
	overturn	0	0	n/a	n/a
	vertical	2	2	3	3
2	burial	0	0	0	0
	lateral	0	1	1	1
	overturn	1	1	1	1
	vertical	0	0	0	0
3	burial	0	0	3	3
	lateral	1	0	1	0
	overturn	1	1	n/a	n/a
	vertical	0	3	3	3
4	burial	1	2	1	2
	lateral	1	0	0	0
	overturn	1	1	1	n/a
	vertical	1	2	2	3
5	burial	0	0	0	0
	lateral	0	1	1	1
	overturn	0	0	0	0
	vertical	0	0	0	0
6	burial	0	0	1	0
	lateral	1	1	0	0
	overturn	1	1	1	n/a
	vertical	0	0	1	3
7	burial	1	2	1	2
	lateral	0	0	0	0
	overturn	0	0	1	1
	vertical	1	1	0	1
8	burial	0	0	1	1
	lateral	1	0	1	1
	overturn	1	1	1	1
	vertical	3	0	3	3
9	burial	2	2	1	2
	lateral	1	1	1	1
	overturn	1	1	1	1
	vertical	2	2	3	3

Appendix I continued

ID	Variable	5-2005	8-2005	7-2006	9-2006
10	burial	0	2	not found	not found
	lateral	1	1		
	overturn	1	1		
	vertical	1	2		
11	burial	0	1	0	1
	lateral	1	1	1	1
	overturn	0	0	0	0
	vertical	0	0	0	2
12	burial	2	2	not found	not found
	lateral	1	0		
	overturn	n/a	1		
	vertical	3	2		
13	burial	2	3	not found	not found
	lateral	*	1		
	overturn	0	0		
	vertical	1	1		
14	burial	0	1	1	1
	lateral	1	1	1	1
	overturn	1	PI	0	0
	vertical	2	0	1	2
15	burial	not found	3	2	2
	lateral		1	1	1
	overturn		0	n/a	n/a
	vertical		1	3	3

Appendix J. Penny data from Site A, DMN.

ID	Variable	8-2005	9-2005	10-2005	7-2006	9-2006
1	burial	NP	0	under snow	0	0
	lateral	NP	1		0	0
	overturn	0	0		0	0
	vertical	NP	0		0	0
2	burial	not found	2	under snow	3	2
	lateral		1		1	0
	overturn		0		0	0
	vertical		0		1	1
3	burial	not found	3	under snow	2	2
	lateral		0		0	0
	overturn		n/a		n/a	n/a
	vertical		3		3	3
4	burial	not found	not found	not found	3	2
	lateral				1	0
	overturn				0	0
	vertical				1	1
5	burial	1	1	under snow	0	0
	lateral	0	1		1	0
	overturn	0	0		1	1
	vertical	0	1		0	0
6	burial	NP	PI	under snow	1	0
	lateral	NP	PI		*	0
	overturn	0	0		0	0
	vertical	NP	0		0	0
7	burial	3	2	under snow	3	3
	lateral	1	0		1	1
	overturn	0	0		0	n/a
	vertical	1	1		1	3
8	burial	3	3	3	3	2
	lateral	1	0	0	0	1
	overturn	n/a	n/a	n/a	n/a	1
	vertical	3	3	3	3	3
9	burial	3	3	3	2	2
	lateral	1	0	0	0	0
	overturn	n/a	n/a	n/a	1	1
	vertical	3	3	3	3	3

Appendix J continued

ID	Variable	8-2005	9-2005	10-2005	7-2006	9-2006
10	burial lateral overturn vertical	not found	not found	not found	2 1 n/a 3	2 0 n/a 3
11	burial lateral overturn vertical	NP NP 0 NP	1 * 0 0	under snow	2 1 0 1	2 0 0 1
12	burial lateral overturn vertical	not found	not found	not found	3 1 n/a 3	no photo
13	burial lateral overturn vertical	not found	not found	3 * 0 1	2 0 0 1	2 0 0 2
14	burial lateral overturn vertical	not found	no photo	not found	3 * n/a 3	3 0 n/a 3
15	burial lateral overturn vertical	not found	not found	not found	3 1 n/a 3	3 0 n/a 3

Appendix K. Penny data from Site B, DMN.

ID	Variable	7-2004	7-2006	9-2006
1	burial	1	3	3
	lateral	*	*	0
	overturning	0	0	0
	vertical	0	1	1
2	burial	1	1	1
	lateral	*	*	0
	overturning	1	0	0
	vertical	1	1	1
3	burial	0	1	2
	lateral	*	*	0
	overturning	1	0	0
	vertical	0	1	2
4	burial	1	1	1
	lateral	*	*	0
	overturning	1	0	0
	vertical	1	1	1
5	burial	NP	2	3
	lateral	NP	*	1
	overturning	0	1	1
	vertical	NP	1	1
6	burial	1	3	1
	lateral	*	*	0
	overturning	0	1	1
	vertical	1	0	0
7	burial	0	1	1
	lateral	*	*	0
	overturning	0	1	1
	vertical	0	0	0
8	burial	0	3	1
	lateral	*	*	0
	overturning	1	1	1
	vertical	0	1	1
9	burial	0	2	2
	lateral	*	*	0
	overturning	1	0	0
	vertical	0	3	3

Appendix K continued

ID	Variable	7-2004	7-2006	9-2006
10	burial	0	1	2
	lateral	*	*	0
	overturning	0	1	1
	vertical	0	2	1
11	burial	0	not found	1
	lateral	*		1
	overturning	0		0
	vertical	0		1
12	burial	0	2	2
	lateral	*	*	0
	overturning	0	0	0
	vertical	0	0	1
13	burial	0	1	2
	lateral	*	*	0
	overturning	0	0	0
	vertical	1	3	3
14	burial	0	2	2
	lateral	*	*	0
	overturning	0	1	1
	vertical	0	1	2
15	burial	1	3	3
	lateral	*	*	0
	overturning	0	0	0
	vertical	2	1	1

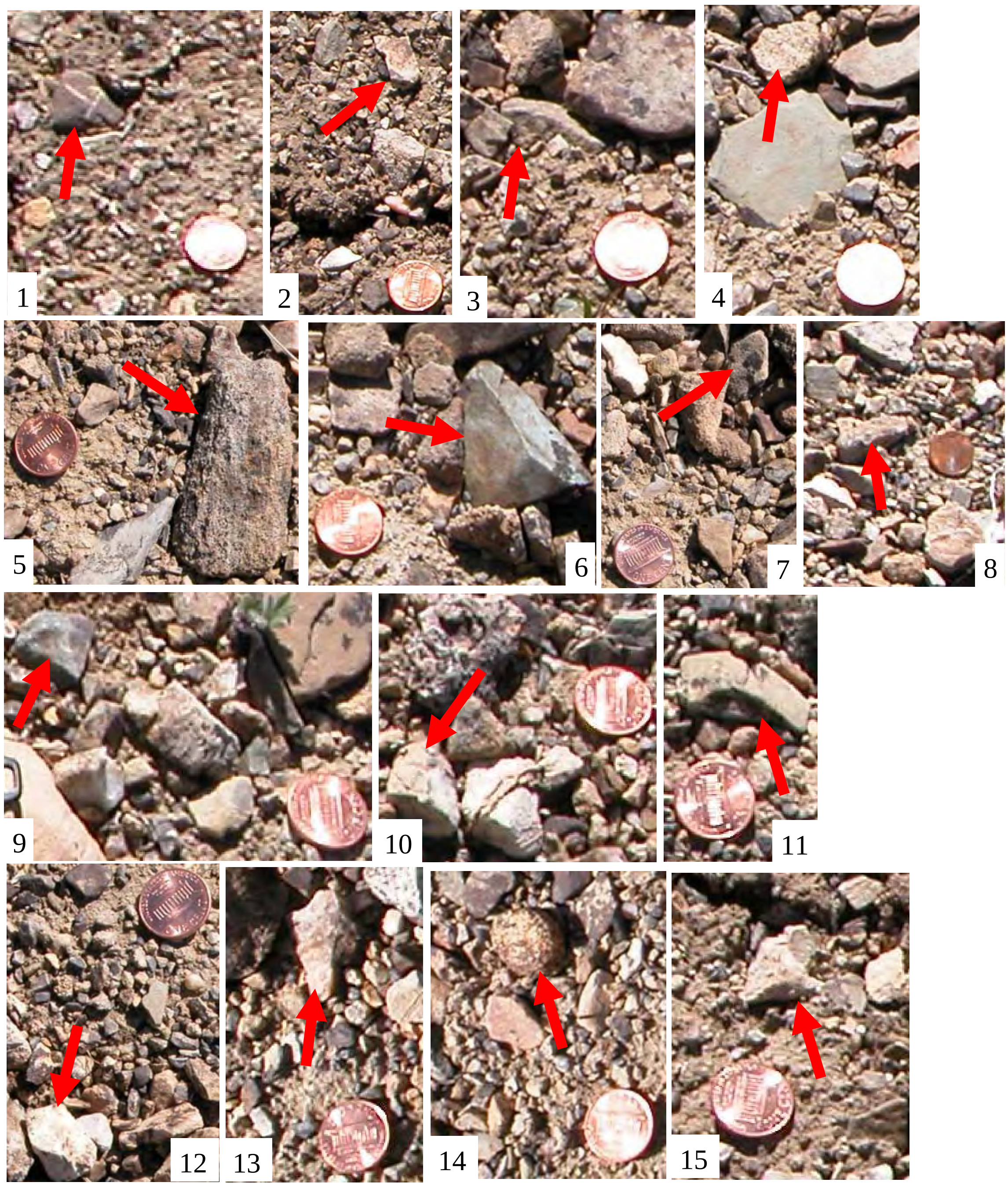
Appendix L. Penny data from Site I, SP

ID	Variable	7-2006
1	burial	0
	lateral	1
	overturning	1
	vertical	1
2	burial	0
	lateral	1
	overturning	1
	vertical	0
3	burial	0
	lateral	1
	overturning	1
	vertical	0
4	burial	2
	lateral	1
	overturning	1
	vertical	0
5	burial	3
	lateral	1
	overturning	0
	vertical	0
6	burial	1
	lateral	1
	overturning	0
	vertical	1
7	burial	0
	lateral	1
	overturning	0
	vertical	0
8	burial	Not found
	lateral	
	overturning	
	vertical	
9	burial	1
	lateral	0
	overturning	1
	vertical	1

Appendix L continued

ID	Variable	7-2006
10	burial	0
	lateral	1
	overturning	0
	vertical	1
11	burial	0
	lateral	1
	overturning	0
	vertical	1
12	burial	0
	lateral	1
	overturning	0
	vertical	0
13	burial	0
	lateral	1
	overturning	1
	vertical	0
14	burial	0
	lateral	1
	overturning	0
	vertical	0
15	burial	2
	lateral	1
	overturning	n/a
	vertical	3

Appendix M. Clast photographs, Site 1, DMS, photos from 2003.



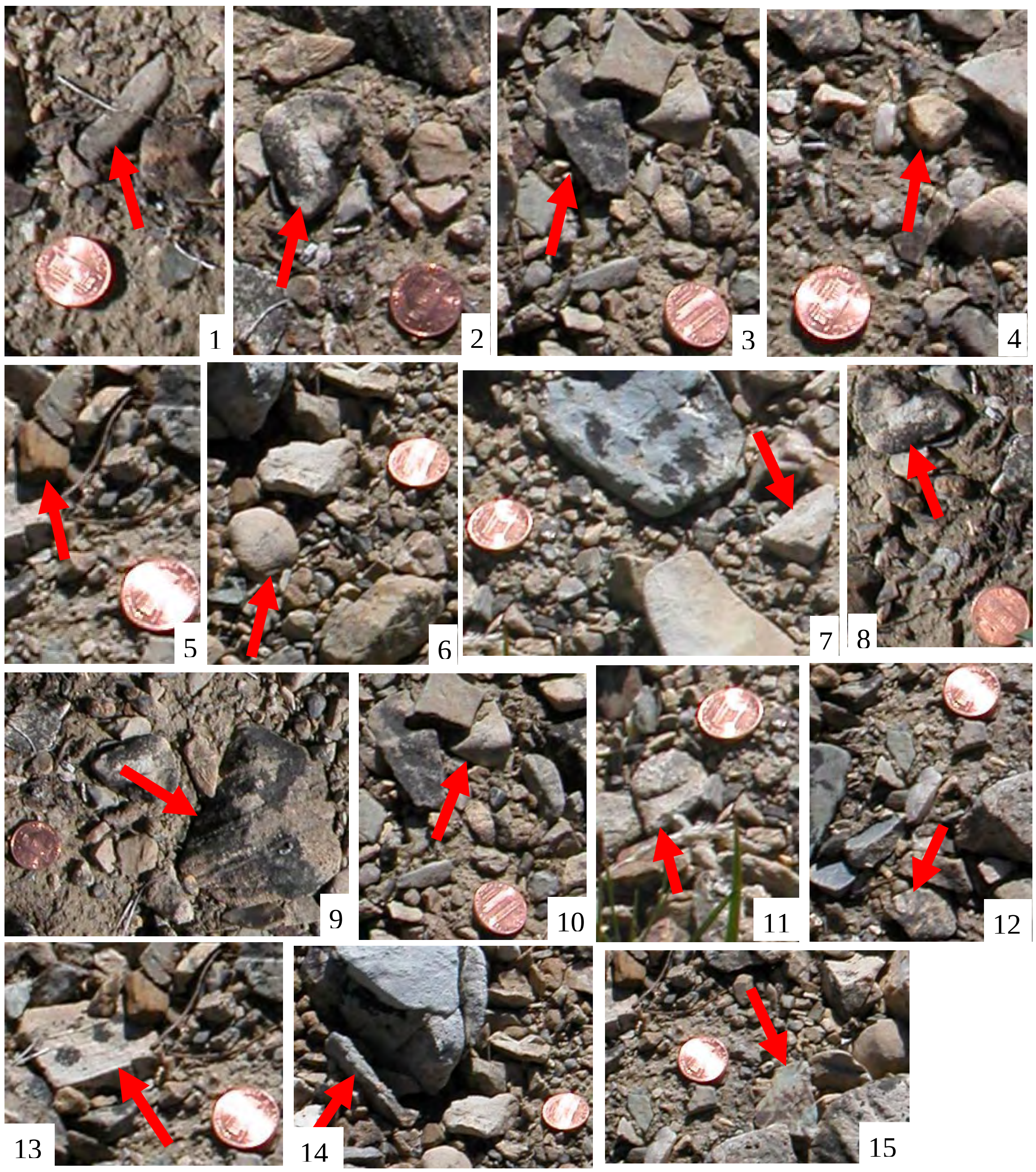
Appendix N. Clast data from Site 1, DMS.

ID	Variable	Jul-04	Aug-05	Jul-06	Sep-06
1	Burial	-2	0	0	0
	Rotation (°)	(-15) 345	(-35) 310	(-15) 295	(-5) 290
	Overturn	0	0	0	0
	Lateral (cm)	2.85	2.85	0	0
2	Burial	0	0	not found	not found
	Rotation (°)	60 (60)	(-20) 40		
	Overturn	0	0		
	Lateral (cm)	0	<1		
3	Burial	-1	0	0	0
	Rotation (°)	85	(50) 130	(-15) 115	0
	Overturn	1	0	1	0
	Lateral (cm)	<1	<1	0	0
4	Burial	0	0	0	0
	Rotation (°)	0	0	(-15) 345	0
	Overturn	0	0	0	0
	Lateral (cm)	<1	0	<1	0
5	Burial	-1	2	0	0
	Rotation (°)	(-50) 310	0	0	(-15) 295
	Overturn	0	0	0	0
	Lateral (cm)	0	0	0	0
6	Burial	2	2	1	1
	Rotation (°)	0	(15) 15	(30) 45	0
	Overturn	0	0	1	1
	Lateral (cm)	0	0	0	0
7	Burial	0	0	0	0
	Rotation (°)	(-50) 310	0	(10) 320	0
	Overturn	0	0	0	0
	Lateral (cm)	0	0	<1	<1
8	Burial	0	0	0	0
	Rotation (°)	(30) 330	(-50) 280	0	(-30) 250
	Overturn	1	1	1	0
	Lateral (cm)	0	0	0	0
9	Burial	0	0	0	0
	Rotation (°)	(-50) 310	0	0	0
	Overturn	0	0	0	0
	Lateral (cm)	<1	0	<1	0

Appendix N continued

ID	Variable	Jul-04	Aug-05	Jul-06	Sep-06
10	Burial	0	not found	0	0
	Rotation (°)	(110) 110		(-20) 90	0
	Overturn	1		1	0
	Lateral (cm)	<1		0	0
11	Burial	0	0	0	0
	Rotation (°)	0	0	320	310
	Overturn	0	0	0	0
	Lateral (cm)	0	0	0	0
12	Burial	0	0	0	0
	Rotation (°)	(-55) 305	(75) 20	(75) 95	(-25) 70
	Overturn	0	1	1	0
	Lateral (cm)	0	0	0	0
13	Burial	0	not found	not found	not found
	Rotation (°)	(-50) 310			
	Overturn	0			
	Lateral (cm)	0			
14	Burial	0	0	0	0
	Rotation (°)	0	0	0	0
	Overturn	1	1	1	0
	Lateral (cm)	0	0	0	0
15	Burial	0	0	0	0
	Rotation (°)	(10) 10	0	(50) 60	0
	Overturn	0	0	0	1
	Lateral (cm)	0	0	0	0

Appendix O. Clast photographs, Site 2, DMS, photos from 2003.



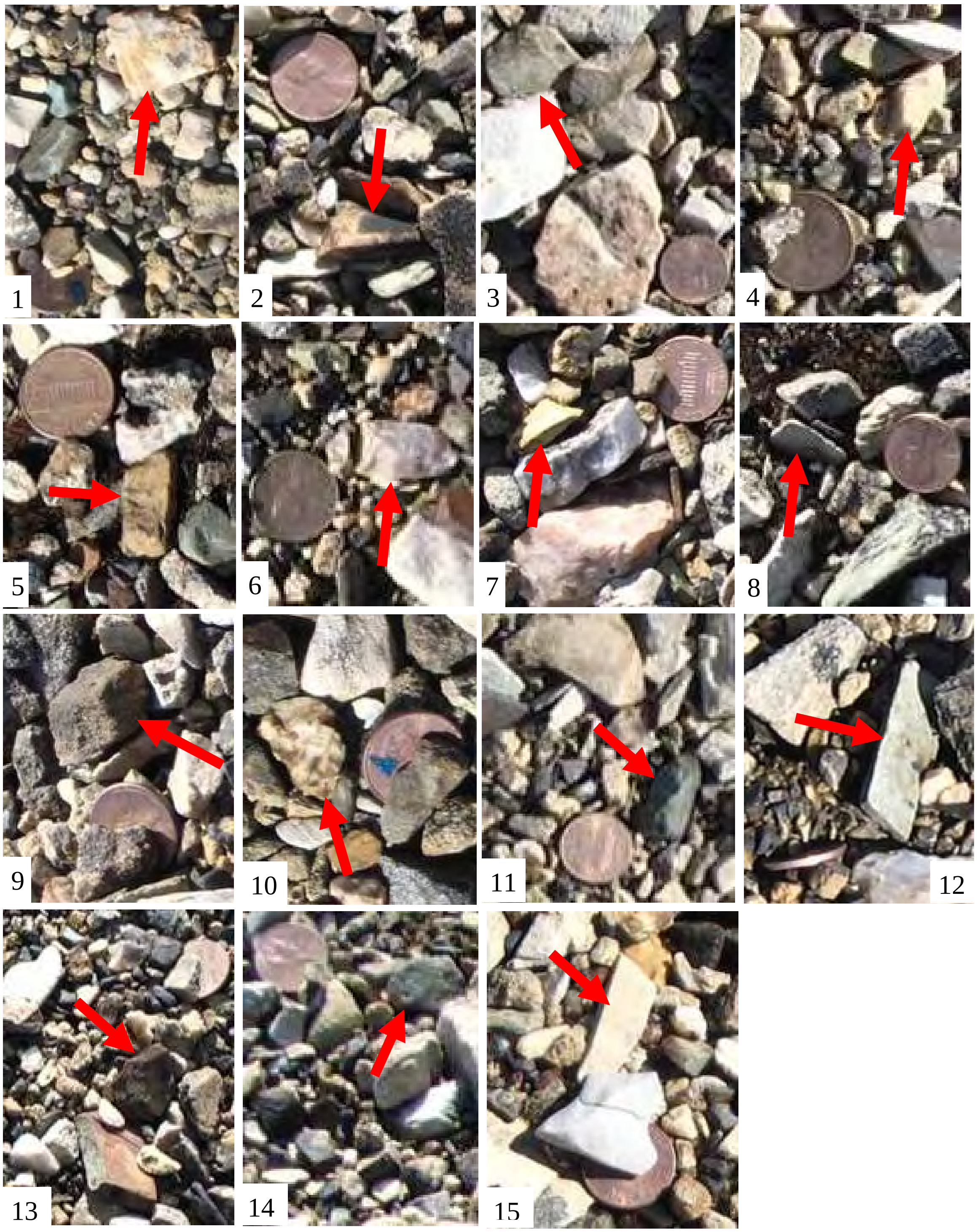
Appendix P. Clast data from Site 2, DMS.

ID	Variable	Jul-04	Aug-05	Jul-06	Sep-06
1	Burial	-2	0	0	0
	Rotation (°)	(90) 90	(35) 125	(10) 135	(10) 145
	Overturn	1	0	1	0
	Lateral (cm)	0	0	0	0
2	Burial	0	0	0	0
	Rotation (°)	0	(-20) 340	(-45) 295	0
	Overturn	0	0	0	0
	Lateral (cm)	<1	<1		0
3	Burial	0	0	0	0
	Rotation (°)	(115) 115	0	0	0
	Overturn	0	0	0	0
	Lateral (cm)	0	<1	<1	0
4	Burial	0	0	0	0
	Rotation (°)	60	(70) 135	(15) 140	(35) 175
	Overturn	0	1	1	0
	Lateral (cm)	<1	<1	<1	0
5	Burial	0	0	0	0
	Rotation (°)	0	0	70 (70)	0
	Overturn	1	1	1	0
	Lateral (cm)	<1	<1	<1	0
6	Burial	0	0	0	0
	Rotation (°)	0	0	0	0
	Overturn	0	0	0	0
	Lateral (cm)	0	0	<1	0
7	Burial	0	NP	0	0
	Rotation (°)	(-30) 330	NP	(-80) 250	(10) 260
	Overturn	0	NP	0	0
	Lateral (cm)	<1	NP	<1	0
8	Burial	0	0	0	0
	Rotation (°)	0	(-20) 340	(-50) 290	(25) 315
	Overturn	0	0	0	0
	Lateral (cm)	<1	<1	0	0
9	Burial	0	0	0	0
	Rotation (°)	20 (20)	0	0	0
	Overturn	0	0	0	0
	Lateral (cm)	0	0	0	0

Appendix P continued

ID	Variable	Jul-04	Aug-05	Jul-06	Sep-06
10	Burial	-1	1	1	0
	Rotation (°)	0	(-20) 340	0	0
	Overturn	0	1	1	1
	Lateral (cm)	0	<1	<1	0
11	Burial	1	0	0	0
	Rotation (°)	(20) 340	0	0	0
	Overturn	0	0	0	0
	Lateral (cm)	<1	0	0	0
12	Burial	0	0	1	2
	Rotation (°)	(25) 25	0	(10) 35	(15) 50
	Overturn	0	0	0	0
	Lateral (cm)	0	<1	<1	0
13	Burial	0	0	0	0
	Rotation (°)	(5) 5	0	(15) 20	0
	Overturn	0	0	0	0
	Lateral (cm)	0	0	0	<1
14	Burial	-1	0	0	0
	Rotation (°)	(-35) 325	(-15) 310	(-30) 280	0
	Overturn	1	0	0	0
	Lateral (cm)	0	0	0	0
15	Burial	0	0	0	0
	Rotation (°)	(20) 20	(25) 45	0	0
	Overturn	0	0	0	0
	Lateral (cm)	0	0	0	0

Appendix Q. Clast photographs, Site 3, DMS, 2005 photos, except clast 15 (2006).



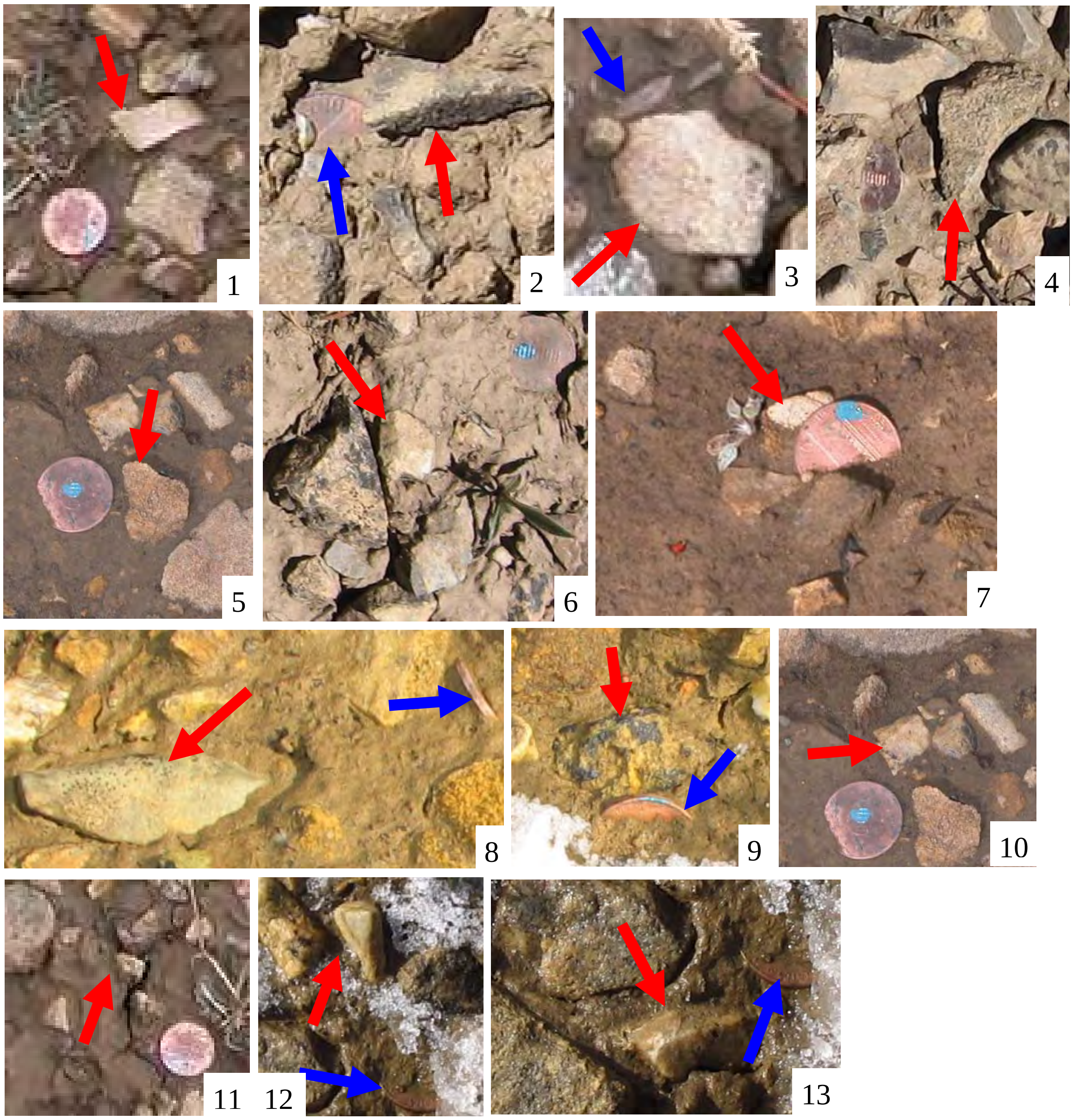
Appendix R. Clast data from Site 3, DMS.

ID	Variable	Aug-05	Jul-06	Sep-06
1	Burial	-2	0	0
	Rotation (°)	0	0	0
	Overturn	0	0	0
	Lateral (cm)	0	<1	0
2	Burial	0	0	0
	Rotation (°)	0	0	0
	Overturn	1	1	0
	Lateral (cm)	0	0	0
3	Burial	0	0	0
	Rotation (°)	0	0	0
	Overturn	0	0	1
	Lateral (cm)	0	0	0
4	Burial	1	1	1
	Rotation (°)	0	0	0
	Overturn	1	1	1
	Lateral (cm)	0	0	0
5	Burial	0	0	0
	Rotation (°)	0	(15) 15	0
	Overturn	0	0	0
	Lateral (cm)	0	0	0
6	Burial	0	1	1
	Rotation (°)	0	0	0
	Overturn	1	0	0
	Lateral (cm)	0	0	0
7	Burial	1	2	1
	Rotation (°)	0	0	0
	Overturn	1	1	0
	Lateral (cm)	0	0	0
8	Burial	1	1	2
	Rotation (°)	0	0	0
	Overturn	0	0	0
	Lateral (cm)	0	0	0
9	Burial	0	0	0
	Rotation (°)	0	0	0
	Overturn	0	0	0
	Lateral (cm)	0	2	0

Appendix R continued

ID	Variable	Aug-05	Jul-06	Sep-06
10	Burial	-1	NP	0
	Rotation (°)	(-35) 325	NP	0
	Overturn	0	NP	0
	Lateral (cm)	0	NP	<1
11	Burial	0	0	0
	Rotation (°)	0	(55) 55	(-10) 45
	Overturn	0	1	1
	Lateral (cm)	0	<1	<1
12	Burial	0	1	NP
	Rotation (°)	(-40) 320	(5) 325	NP
	Overturn	0	0	NP
	Lateral (cm)	<1	<1	NP
13	Burial	0	1	NP
	Rotation (°)	0	0	NP
	Overturn	1	1	NP
	Lateral (cm)	<1	<1	NP
14	Burial	0	1	1
	Rotation (°)	0	0	0
	Overturn	0	1	0
	Lateral (cm)	0	<1	<1
15	Burial	1	Not found	Not found
	Rotation (°)	0		
	Overturn	0		
	Lateral (cm)	0		

Appendix S. Clast photographs, Site A, DMN, see text below for photo dates.



9/2005 photos for clasts 1, 3, 5, 7, 10, and 11; 10/2005 photos for clasts 8, 9, 12, 13, and 15; 7/2006 for clasts 2, 4, 6, and 14. Red arrows: clasts; blue arrows: pennies.

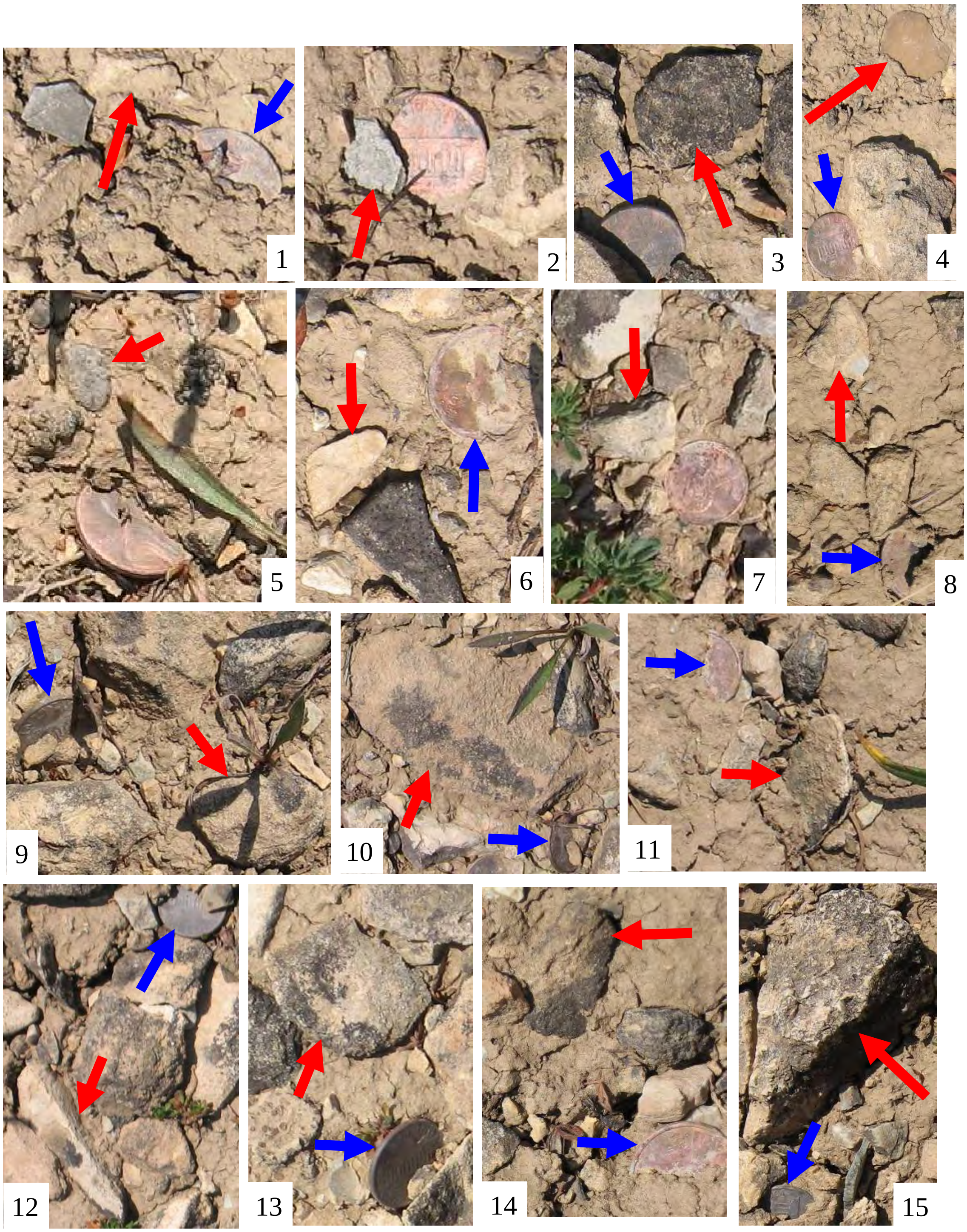
Appendix T. Clast data from Site A, DMN.

ID	Variable	Oct-05	Jul-06	Sep-06
1	Burial	under snow	0	0
	Rotation (°)		0	0
	Overturn		1	0
	Lateral (cm)		0	0
2	Burial	under snow	0	0
	Rotation (°)		0	0
	Overturn		0	0
	Lateral (cm)		0	0
3	Burial	under snow	0	0
	Rotation (°)		0	0
	Overturn		0	0
	Lateral (cm)		0	0
4	Burial	under snow	PI	0
	Rotation (°)		PI	0
	Overturn		PI	0
	Lateral (cm)		PI	0
5	Burial	under snow	0	0
	Rotation (°)		0	(-10) 350
	Overturn		0	0
	Lateral (cm)		0	0
6	Burial	under snow	PI	0
	Rotation (°)		PI	0
	Overturn		PI	0
	Lateral (cm)		PI	0
7	Burial	under snow	-2	3
	Rotation (°)		(10) 10	n/a
	Overturn		0	1
	Lateral (cm)		0	0
8	Burial	3	1	1
	Rotation (°)	0	0	0
	Overturn	0	0	0
	Lateral (cm)	0	0	0
9	Burial	2	2	0
	Rotation (°)	0	0	0
	Overturn	0	0	0
	Lateral (cm)	0	0	0

Appendix T continued

ID	Variable	Oct-05	Jul-06	Sep-06
10	Burial	under snow	2	2
	Rotation (°)		(-20) 340	0
	Overturn		0	0
	Lateral (cm)		0	0
11	Burial	under snow	2	1
	Rotation (°)		0	(20) 20
	Overturn		1	0
	Lateral (cm)		0	0
12	Burial	0	not found	not found
	Rotation (°)	0		
	Overturn	0		
	Lateral (cm)	0		
13	Burial	2	2	1
	Rotation (°)	0	0	0
	Overturn	0	0	0
	Lateral (cm)	0	0	0
14	Burial	under snow	2	0
	Rotation (°)		0	0
	Overturn		0	0
	Lateral (cm)		0	0
15	Burial	under snow	2	2
	Rotation (°)		0	0
	Overturn		0	0
	Lateral (cm)		0	0

Appendix U. Clast photographs, Site B, DMN, photos from July 2006.



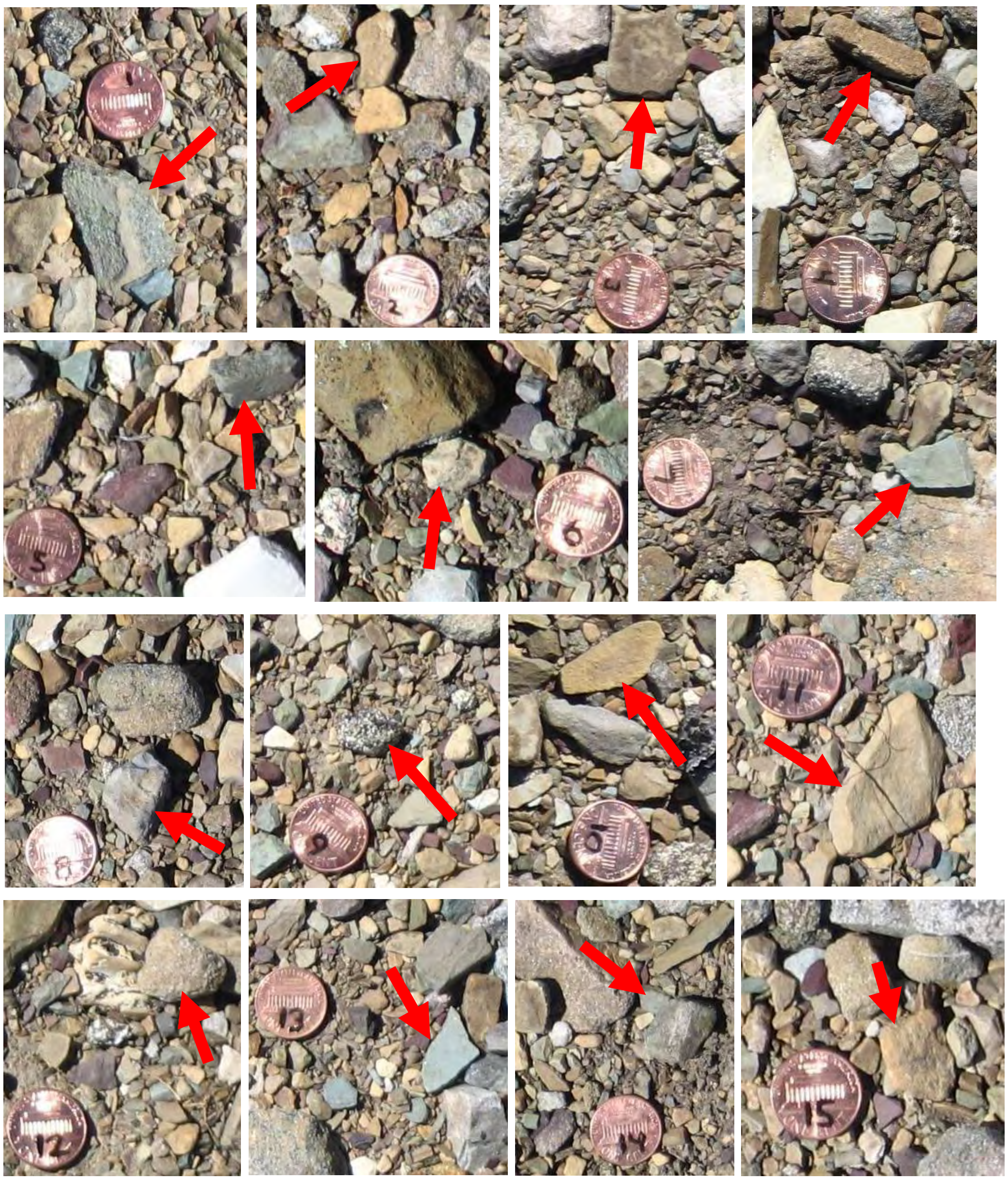
Appendix V. Clast data from Site B, DMN.

ID	Variable	Sep-06
1	Burial	0
	Rotation (°)	0
	Overturn	0
	Lateral (cm)	0
2	Burial	-1
	Rotation (°)	0
	Overturn	0
	Lateral (cm)	0
3	Burial	0
	Rotation (°)	0
	Overturn	0
	Lateral (cm)	0
4	Burial	-1
	Rotation (°)	0
	Overturn	0
	Lateral (cm)	0
5	Burial	0
	Rotation (°)	0
	Overturn	0
	Lateral (cm)	0
6	Burial	0
	Rotation (°)	0
	Overturn	0
	Lateral (cm)	0
7	Burial	0
	Rotation (°)	0
	Overturn	0
	Lateral (cm)	0
8	Burial	-1
	Rotation (°)	0
	Overturn	0
	Lateral (cm)	0
9	Burial	0
	Rotation (°)	0
	Overturn	0
	Lateral (cm)	0

Appendix V continued

ID	Variable	Sep-06
10	Burial	-1
	Rotation (°)	0
	Overturn	0
	Lateral (cm)	0
11	Burial	0
	Rotation (°)	0
	Overturn	0
	Lateral (cm)	0
12	Burial	0
	Rotation (°)	0
	Overturn	0
	Lateral (cm)	0
13	Burial	0
	Rotation (°)	0
	Overturn	0
	Lateral (cm)	0
14	Burial	0
	Rotation (°)	0
	Overturn	0
	Lateral (cm)	0
15	Burial	0
	Rotation (°)	0
	Overturn	0
	Lateral (cm)	0

Appendix W. Clast photographs, Site I, SP, photos from 2005.



Appendix X. Clast data from Site I, SP.

ID	Variable	Jul-06
1	Burial	0
	Rotation (°)	(40) 40
	Overturn	1
	Lateral (cm)	3.8
2	Burial	0
	Rotation (°)	(75) 75
	Overturn	1
	Lateral (cm)	2.8
3	Burial	not found
	Rotation (°)	
	Overturn	
	Lateral (cm)	
4	Burial	2
	Rotation (°)	(25) 25
	Overturn	1
	Lateral (cm)	3.8
5	Burial	3
	Rotation (°)	0
	Overturn	1
	Lateral (cm)	0
6	Burial	1
	Rotation (°)	(-50) 310
	Overturn	0
	Lateral (cm)	1.4
7	Burial	0
	Rotation (°)	(125) 125
	Overturn	0
	Lateral (cm)	3.8
8	Burial	0
	Rotation (°)	(70) 70
	Overturn	1
	Lateral (cm)	3.8
9	Burial	1
	Rotation (°)	(-70) 290
	Overturn	1
	Lateral (cm)	4.8

Appendix X continued

ID	Variable	7-2006
10	Burial	0
	Rotation (°)	(180) 180
	Overturn	0
	Lateral (cm)	5.7
11	Burial	0
	Rotation (°)	0
	Overturn	0
	Lateral (cm)	1
12	Burial	0
	Rotation (°)	(30) 30
	Overturn	1
	Lateral (cm)	5.7
13	Burial	0
	Rotation (°)	(-30) 330
	Overturn	1
	Lateral (cm)	5.7
14	Burial	0
	Rotation (°)	(-40) 320
	Overturn	0
	Lateral (cm)	0
15	Burial	2
	Rotation (°)	(70) 70
	Overturn	1
	Lateral (cm)	0

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