Géographie physique et Quaternaire

Talus fabric, clast morphology, and botanical Indicators of Slope Processes on the Chaos Crags (California Cascades), U.S.A.

Francisco L. Pérez

Résumé de l'article

Les Chaos Crags, un ensemble de dômes de dacite, ont subi des glissements de débris volcaniques vers 1675 ap. J.-C. qui ont laissé un volumineux dépôt et une cicatrice sur le flanc nord, maintenant recouverte de talus d'éboulis. On étudie ici les variations spatiales de l'organisation des éléments (fabrique), la morphologie des talus et les processus géomorphologiques présentement actifs. Le talus présente un profil en deux segments : le segment supérieur, plus raide, présente un profil rectiligne tandis que le segment inférieur est concave et plus court. Les débris sont granoclassés à la fois verticalement (les plus gros fragments vers le bas des talus) et horizontalement (les plus grosses particules sous les parois). Le classement selon la forme est moins défini, mais la sphéricité augmente et l'allongement diminue vers le bas. L'orientation des fragments dans le haut du talus (grands axes parallèles au plan et à la direction de la pente) montre que les fragments se sont déplacés par glissement, alors que les blocs de la base ont été déposés par éboulement, ce qui entraîne une orientation de type isotrope. Les observations de terrain et les données botaniques démontrent l'importance des glissements qui se produisent en raison de la présence d'une grande quantité de blocaille dans la partie supérieure. La comparaison avec d'autres versants semblables et la photographie répétée indique que le talus des Chaos Crags s'est formé rapidement après l'effondrement du dôme, alors que de nombreux débris se sont accumulés sous des murs rocheux instables. Le talus a connu une faible sédimentation au cours du XX\textsuperscript{e} siècle et a été altéré par divers mouvements de masse, incluant les avalanches et les glissements de terrain.
TALUS FABRIC, CLAST MORPHOLOGY, AND BOTANICAL INDICATORS OF SLOPE PROCESSES ON THE CHAOS CRAGS (CALIFORNIA CASCADES), U.S.A.

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ABSTRACT  The Chaos Crags, a group of dacite domes in the Cascade Mtns (California), were affected by volcanic debris avalanches ca. 1675 A.D.; these left a sizable deposit and a scar on the north mountain flank, now covered by talus. This report examines the fabric and morphology of talus debris, their spatial variation, and the geomorphic processes presently affecting the slope. The talus presents a bi-segmented profile with a steep upper rectilinear segment and a shorter concave, basal zone. Debris are sorted by size both along (larger clasts downslope) and across the talus (larger particles below the cliffs). Shape sorting is weaker, but clast sphericity increases, and elongation decreases, toward the foottalose. Upper-talus fabrics (long axes parallel to talus plane and slope) show that clasts there move by sliding, while basal blocks are deposited by rockfall, which causes more isotropic fabrics. Field observations and botanical evidence indicate the overall significance of grain flows, which are prevalent due to an abundant supply of rubble on the upper talus. Comparison with similar recent slopes and repeat photography suggest the Chaos talus formed swiftly following dome collapse, when much debris may have collected below the unstable rockwalls. The talus has experienced only modest sedimentation during the 20th century, and is currently affected by “normal” mass-wasting processes, which also include snow avalanches and debris flows.

RÉSUMÉ  Relevés botaniques, granulométrie, forme et organisation des débris sur les talus d’éboulis en tant qu’indicateurs des processus dans les Chaos Crags (monts Cascade, Californie, U.S.A.). Les Chaos Crags, un ensemble de dômes de dacite, ont subi des glissements de débris volcaniques vers 1675 ap. J.-C. qui ont laissé un volumineux dépôt et une cicatrice sur le flanc nord, maintenant recouverte de talus d’éboulis. On étudie ici les variations spatiales de l’organisation des éléments (fabriques), la morphologie des talus et les processus géomorphologiques présentement actifs. Le talus présente un profil en deux segments: le segment supérieur, plus raide, présente un profil rectiligne tandis que le segment inférieur est concave et plus court. Les débris sont granoclassés à la fois verticalement (les plus gros fragments vers le bas des talus) et horizontallement (les plus grosses particules sous les parois). Le classement selon la forme est moins défini, mais la sphéricité augmente et l’allongement diminue vers le bas. L’orientation des fragments dans le haut du talus (grands axes parallèles au plan et à la direction de la pente) montre que les fragments se sont déplacés par glissement, alors que les blocs de la base ont été déposés par éboulis, ce qui entraîne une orientation de type isotropic. Les observations de terrain et les données botaniques démontrent l’importance des glissements qui se produisent en raison de la présence d’une grande quantité de blocaille dans la partie supérieure. La comparaison avec d’autres versants semblables et la photographie répétée indique que le talus des Chaos Crags s’est formé rapidement après l’effondrement du dôme, alors que de nombreux débris se sont accumulés sous des murs rocheux instables. Le talus a connu une faible sédimentation au cours du XXe siècle et a été altéré par divers mouvements de masse, incluant les avalanches et les glissements de terrain.

RESUMEN  Morfología y orientación de derrubios clásticos, e indicadores botánicos de procesos de pendiente en Chaos Crags (Cascades, California). Los Chaos Crags, un grupo de domos de dacita en las Montañas Cascades (California), fueron afectados por varias avalanchas detríticas volcánicas ca. 1675 D.C.; éstas dejaron un gran depósito de derrubios y una cicatriz en la ladera norte de la montaña, hoy día cubierta por talos. Se examina aquí la morfología y la orientación de las partículas del talo, la variación espacial de éstas, y los procesos geomorfológicos que actualmente afectan la pendiente. El talo muestra un perfil bi-segmentado con una porción superior rectilínea y empinada, y una zona cóncava basal más corta. Los derrubios están segregados por tamaño tanto a lo largo (clastos mayores en la base de la montaña) como al través de la pendiente (partículas mayores debajo de las paredes rocosas). Los fragmentos también están segregados por forma; su esfericidad incrementa hacia la base del talo, donde la elongación de las partículas es menor. La orientación clástica en el talo superior (ejes paralelos al plano y a la dirección de la pendiente) indica que las piedras se mueven allí por deslizamiento, mientras que los bloque al pie del flanco son depositados por caídas de rocas, que causan una orientación mas isotrópica. Las observaciones de campo y la evidencia botánica indican la importancia de los movimientos secos pelícuales, asociados con un abundante suministro de derrubios en el alto talo. Comparación con otras pendientes recientes similares y foto-repetición sugieren que el talo en Chaos Crags se formó rápidamente tras el colapso del domo, cuando grandes cantidades de fragmentos deben haberse acumulado debajo de las inestables paredes rocosas. El talo ha experimentado sólo una modesta sedimentación durante el siglo 20, y hoy día es afectado por procesos geomorfológicos ‘normales’, que también incluyen aludes de nieve y flujos de barro.
INTRODUCTION

Catastrophic rockfalls (Porter and Orobelli, 1980) and associated deposits have received a great deal of attention in recent years. They are given different names, such as catastrophic rock- or land-slides, rock- or rockfall-avalanches, rockslide-avalanches, or sturzstroms (Crandell and Fahnestock, 1965; Shreve, 1966; Browning, 1973; Eisbacher, 1979; Butler et al., 1986; Dawson et al., 1986). These high-magnitude events are often triggered by earthquake activity. In addition, volcanic activity may cause similar large mass-wasting events, which are then more appropriately called volcanic debris avalanches (VDAs) (Siebert, 1984). Attention has focused on the causes of catastrophic rockfalls and on the deposits left by them. Many studies have described rockfall deposits; in North America, recent or ancient debris deposits are found in several mountain ranges, including the Montana Rockies (Butler et al., 1986), the Chugach Mountains of Alaska (Shreve, 1966) and the Mackenzie Mountains of northwestern Canada (Eisbacher, 1979). Sizable VDA deposits are common in the volcanic Cascade Range. Areas recently affected include Mount St. Helens (Voight et al., 1983) and Little Tahoma Peak, Washington (Crandell and Fahnestock, 1965). Some studies, while focusing on the debris deposits, also contain cross-sectional views that include the source area, but none - to my knowledge - ever investigated the characteristics of the ‘detachment scar’, or of the talus slopes produced on the mountain flank by the catastrophic rockfall events, or their evolution with time.

The Chaos Crags is a group of dacite domes in the Cascades of northern California, where a series of VDAs ca. 1675 A.D. produced a large debris deposit (the ‘Chaos Jumbles’), which covers nearly 8 km² and has a thickness of up to 40 m (Crandell et al., 1974). The Chaos Jumbles have been studied by several researchers, starting with Howel Williams in 1928. Details about the geology of the Chaos Crags and Jumbles are given below, but it is pertinent to note that previous research has exclusively dealt with the Jumbles, and that little attention has been given to the talus cover on the scarred mountain flank below the collapsed dacite dome.

This study reports on the morphology of the talus aprons that have accumulated on the collapsed northern flank of the Chaos Crags since VDAs took place three centuries ago, and on the geomorphic processes that shape this talus at present. I will specifically examine the spatial variation of clast size, shape, and fabric, and of talus texture (i. e., type of talus surface according to predominant particle size [Caine, 1967; Pérez, 1986]). I will then try to correlate these characteristics with the activity of different geomorphic processes. I have previously (Pérez, 1988a, b, 1989, 1990a) reported on the spatial trends of these parameters, and on the geomorphic agents which may influence them, on talus slopes on and near Lassen Peak. Those papers dealt with slopes that presumably have formed gradually by rockwall weathering during the Holocene. This study at Chaos Crags provides an unusual opportunity to generally contrast talus slopes of similar lithology, affected by comparable environmental parameters, but which have developed over widely different time periods. Site structure and topography clearly indicate that dome collapse and the VDAs removed any previous talus that might have covered the mountain flank (Williams, 1928, 1929, 1932). Three contrasting models of debris supply to the Chaos talus may be considered: (a) Some talus rubble - or perhaps even the bulk of it - may have been added by the VDAs; alternatively, (b) most of the slope debris were quickly deposited following the rockfall events; or (c) talus sediments have been deposited by gradual dome erosion during the last 300+ years. If talus debris were added by VDA events or soon afterwards, the slope may still display some significant differences from nearby ‘normal’ talus slopes gradually developed below dacite domes, but if the rubble was incrementally deposited post-collapse, few or no morphological differences might be evident.

Particle morphology and sorting are useful indicators of geomorphic processes acting on talus slopes. Many studies report increasing particle size downslope (Rapp, 1960a, b; Gardner, 1972; Bones, 1973; Albjär et al., 1979; Pérez, 1986, 1988b, 1989). This occurs because: (1) large clasts gather momentum and bounce to the talus base; (2) this creates an upslope gradient of lower surface roughness; due to frictional resistance, other moving debris tend to stop near clasts of similar caliber, further reinforcing the sorting trends; (3) any small particles that reach the footslope fall in the openings between blocks (‘sieve effect’; Carniel and Scheidegger, 1974).

Less often, a ‘reversed’ particle sorting (increasing clast size to the talus top) is found. This may eventually occur as debris supply from the rockwalls slowly decreases with time; the gradual reduction of rockwall height would allow most clasts to remain near the talus apex (Rapp, 1960a; Statham, 1973). Alluvial talus, where particles are transported by running water, also shows reversed sorting (Åkerman, 1984). Taluses affected by supravalanche transport develop reversed sorting as well (Hétu, 1995). Some talus slopes may exhibit no consistent downslope sorting (Griffiths, 1959; Caine, 1967). This can result from pronounced down-streaming of independent longitudinal debris ‘tongues’, which tends to produce, instead, a significant sorting across the slope (Brückl et al., 1974; Pérez, 1986). Snow avalanche and debris-flow activity also yields poorly sorted deposits, as such processes may deliver large amounts of fine debris to the footslope (Gardner, 1972; Bones, 1973).

Particle shape variation is less frequently studied, probably because it usually shows a less clear trend than size. McSaveney (1971), Statham (1973), and Pérez (1986) found a gradual downward increase in clast sphericity, related to the greater ability of spherical particles to roll and bounce downhill. An abrupt increase in particle size and sphericity may occur on the basal talus, producing a distinctive ‘basal fringe’ of different particles (Rapp and Fairbridge, 1968). This may be caused by clast gliding over indurated snow, which allows larger and/or more spherical clasts to reach the base of the snow-covered talus (Pérez, 1989; Hétu, 1995). Even when present, shape sorting may be masked by the stronger size sorting (Statham, 1973).
Studies of particle orientation on talus have usually found that most long clast axes are aligned with the slope. Caine (1967) pioneered the study of three-dimensional talus fabrics; many reports have followed (McSaveney, 1971; Albjärf et al., 1979; Pérez, 1988a, b, 1989, 1990a; Hétu et al., 1994, 1995; Hétu, 1995; Van Steijn et al., 1995; Bertran et al., 1997). These studies found that sliding clasts attain an alignment parallel or oblique to the slope and develop a slight uphill imbrication, while rockfall-deposited particles attain an isotropic fabric.

Talus studies often include slope profiles. A few have explored the internal structure of talus by means of seismic resonance techniques (Brückl et al., 1974), but most simply describe the surface topography, focusing on general form, slope gradient, sharp discontinuities and perhaps debris and vegetation cover. Most talus profiles show an upper rectilinear segment and a sharply concave basal portion. This is often ascribed to an exponential (Poisson) distribution of distance of particle travel downslope (Kirby and Stattham, 1975). A more recent model of talus evolution (Francou and Manté, 1990; Francou, 1991) proposes that this topographic change occurs due to different slope processes; the upper talus functions both as deposit and transport surface, while the basal talus is affected exclusively by accumulation. A well-developed basal concavity may also occur from debris transport by snow and slush avalanches, or debris flows (Rapp, 1960a, b; Caine, 1969a). Infrequently, basal convex talus portions are found. These are the result of local debris supply that exceeds the ability of transport processes to distribute debris downslope (Albjärf et al., 1979); slope modification by large scale mass movements (Caine, 1969a); solifluction activity (Pérez, 1986); and presence of moraines (Pérez, 1989), protalus ramparts (Pérez, 1988a) or barriers - such as vegetation - which prevent debris from reaching the footslope (Hétu, 1989). Basal erosion by rivers or rock glaciers might also produce a convex talus profile.

**PHYSICAL SETTING**

Lassen Volcanic National Park (LVNP), is in northern California and has an area of 430 km$^2$ (Fig. 1). Lassen Peak (3193 m) marks the southernmost point of the volcanic Cascade range. The study area, the Chaos Crags (2592 m), is at 40° 32' N, 121° 30' W. The Lassen region is underlain by a complex series of basalt, andesite, and pyroclastic flows, interbedded with glacial deposits (Williams, 1932). Much of LVNP was affected by Holocene volcanic activity; Lassen Peak itself is a dacite dome extruded ~11,000 years BP in late Tioga time. The Chaos Crags were formed about 1200 years ago by extrusion of several dacite domes 5 km north of Lassen Peak (Crandell, 1972). Later, a dome on the NW side of the cluster collapsed, causing catastrophic rockfalls which travelled as far as 4.3 km from the mountain base and produced the Chaos Jumbles, a “chaotic assemblage of gigan- tic, loose, angular blocks” (Williams, 1928: 246). Two straight scar lines clearly mark the 1-km wide segment of the mountain flank which collapsed (Fig. 2). This scarred flank is presently occupied by massive talus deposits. A large depression lies below the talus; this is occupied by a small seasonal meltwater pond (Crags Lake). Williams (1928: 251) considered this depression to “...have been blasted through the loose debris...”, and initially referred to it as a ‘crater’, but later (Williams, 1941) introduced the term ‘explosion caldera’ to refer to the hollow, thus emphasizing its unique volcanic origin (see Siebert, 1984: 165).

Different ages were initially proposed for the Chaos Jumbles. Williams (1928, 1929), based on the age of the oldest trees on the deposit, considered that this had formed 200 years prior to his visit (i.e., ~1725 A.D.). Heath (1959, 1960) argued the Jumbles were actually composed of three different deposits, produced ~270, 750, and 1500 years BP, but was only able to confirm the age of the most recent event (~1690 A.D.) with tree-ring dating. His geologic evidence for the two older deposits was rejected by Crandel et al. (1974: 49), who concluded the Chaos Jumbles “...were formed by three or more high-speed air-cushioned avalanches, all of which occurred about 300 years ago.” (ca. 1675 A.D.). Williams (1928) thought that such event(s) might have been triggered by volcanic or steam explosions, intrusion of another dome, or a strong earthquake. However, the tallest dome in Chaos Crags, directly south from the collapse area (Fig. 1), was emitting steam and gases between 1854 and 1857 (Williams, 1932); this supports the first two hypotheses. Following Siebert (1984: 178), who included the Chaos Crags in his comparative study of Quaternary VDAs, the event that produced the Jumbles is considered to have been a volcanic debris avalanche. A date between 1650 (Siebert, 1984) and 1675 (Crandell et al., 1974) is accepted at present for the deposit.

Peaks in LVNP have enormous talus banks. Williams (1932: 203) noted that: “Scenically, the most striking feature of these mountains is the extraordinary development of talus on their flanks.” Two factors account for this. The talus aprons girdling Lassen Peak, Chaos Crags and other domes originally resulted from the extrusion process, as domes rose through the debris produced by expansion and fracturing of their outer layers (Williams, 1932). The porphyritic hornblende-mica dacites also disintegrate easily, due to a high content of interstitial, intensely fractured glass (Williams, 1932; Pérez, 1988a). The original talus cover on the north flank of Chaos Crags was removed by the debris avalanches, and the present talus has been produced both by the collapse event itself, and by further debris accumulation during the past 320 years.

LVNP has a Mediterranean climate characterized by warm, dry summers, and cool winters with heavy snowfall. During summer, LVNP is under the influence of the North Pacific high, which blocks precipitation. In winter, as the high migrates south, storms move southeasterly into the region from the Aleutian low; thus, most precipitation falls between October and April (Crandell, 1972). Due to this strong seasonality, snowfall may represent 90 to 95 % of the annual total (Major, 1977). The closest station (Manzanita Lake, 1750 m [see Fig. 1]) shows a (1951-1980) mean annual precipitation of 1049 mm; ~91 % of this falls in the October - May period (Parker, 1992). Snow is redistributed by the prevailing westerlies, and sizable snow-fields accumulate on the
more sheltered (N, NE, E) slopes (Crandell, 1972). The snowpack is deep and persistent, and snow usually blankets most of the park from November to May. Snowpack depth at 2500 m commonly reaches 5 to 6.6 m in April/June, decreasing to ~3 m at 2180 m; large snow patches may persist through June above 2000 m (Taylor, 1995).

Mean daily temperatures remain below freezing in LVNP from November to April (Major, 1977). Average monthly temperatures at Manzanita Lake vary from -1.1 °C in January to 16.9 °C in July, but values below 0 °C are recorded at higher elevations in all months (Parker, 1992). Even in August, freezing occurs during 40% of the nights at 2700 m (Pérez, 1988a). Thermal fluctuations are influential in rockfall occurrence, which reaches a peak in spring and early summer, when there is an ample supply of meltwater to most rockwalls (Rapp, 1960a; Gardner, 1970). Temperature oscillations in rockfall occurrence, which reaches a peak in spring and early summer, may also help produce a hard snow crust which facilitates descent of debris over talus (Ward, 1985; Pérez, 1988a, 1990a).

The regional forest line in LVNP is at ≥ 2440 m (Arno and Hammerly, 1984), but small tree islands of whitebark pine (Pinus albicaulis) or mountain hemlock (Tsuga mertensiana) may be found up to ~3060 m (Pérez, 1990b). Owing to the northerly aspect of the talus studied in this report, its local undisturbed forest line is found at an elevation of only ~2130 m (Fig. 2). As the slope extends from about 2025 to 2400 m elevation, it lies right within the timberline zone.

Alpine soils have been scarcely studied in LVNP. Talus slopes on Lassen Peak have sandy-skeletal Lithic and TYPIC Cryorthents (US soil taxonomy; see Soil Survey Staff, 1994) with much gravel (> 60%) and a sandy texture (Pérez, 1989). The bulk of the remaining finer fraction is silt; this suggests that frost weathering - perhaps aided by aeolian deposition - is the main agent of soil formation above timberline.

METHODS

FIELD TECHNIQUES

Four slope profiles were obtained from talus apex to base with compass, clinometer, and a tape stretched between stations at 10-m intervals. The two east transects (A, B) were mainly occupied by large clasts (cobbles, boulders), but the two west ones (C, D) had fewer clasts at the surface, which was covered by gravel or pebbles. The talus surface was sampled on stations every 50 m along the four profiles with a photographic technique (Caine, 1969b; Brückl et al., 1974; Pérez, 1986). Transects A, B, and C had 8 sampling stations each, transect D only 5. At each station, a 100 x 70 cm grid was placed on the talus, and photos taken along a continu-
Clast morphology and fabric along profiles A and B were directly investigated in the field; data come from the same stations above. Fifty contiguous large surface clasts were measured on both sides of the transect, after a procedure by Ward (1985). Parameters determined include three axial lengths (a, b, c axes; Krumbein, 1941), number of clast faces (Caine, 1967), and a axis orientation and plunge (Goudie, 1981).

Detailed observations on activity of slope processes, the deposits left by them, and other evidence of process occurrence were gathered by extensive reconnaissance of the talus, flanks, and summits of the Chaos Crags during five consecutive summers (1989 - 1993). Plants are extensively used in this study as potential indicators of geomorphic activity. Presence and relative abundance of plant species was noted along transects. Specimens of all species found on the talus were collected and classified; taxonomic nomenclature follows Munz and Keck (1970). As part of a related study, the age of the largest 30 trees on the talus was determined by counting annual growth rings from cores extracted about 30 cm - the minimum height needed to turn the increment-borer - above the trunk base. In a few cases, dense low branches made it necessary to core the trees a bit higher. Fifteen specimens of western white (WW) pine (Pinus monticola) and 15 of ponderosa pine (Pinus ponderosa) were taken. The number of years needed for a seedling to reach coring height could not be determined, but based on calibration factors used by Heath (1959) for trees on the Chaos Jumbles and by Taylor (1990) for pines at similar elevations in LVNP, 7 yrs per 30 cm below coring height were added to ring-counted ages.

**ANALYTICAL PROCEDURES**

Regressions between proportional distance along the talus and slope angle were used to assess the degree of concavity along transects (concavity index, Gardner, 1972; Gardner et al., 1983). Trends in debris size were studied with a weighted average particle size (WAPS) (Carniel and Scheidegger, 1974; Pérez, 1989), obtained by multiplying the percentage of the ground surface occupied by each texture (clasts or gravel) by their mean size, and adding these values. Clast volume was calculated on transects A and B, based on the three axial lengths; no correction factor was used for number of clast faces, as all blocks sampled had similar values (6 to 8 faces). Volume is expressed as a nominal diameter or 'diameter of an equivalent sphere' (Folk, 1980) in cm and in the phi (Ø) scale (Caine, 1967). The standard deviation in Ø units was used as a measure of sorting (Folk, 1980). Clast shape was mainly analyzed with three numerical indices: mean sphericity \((c^2/[a \times b])^{3/2}\), elongation \((a/b)\), and flatness \((a + b/2c)\) (Goudie, 1981; Gardiner and Dackombe, 1983). Two additional indices, \((c/a)\) and \((a - b)/[(a - c)]\), were also calculated and used to project clast-shape distributions on ternary diagrams (Folk, 1980) (see Fig. 9). Data sets for all parameters were tested for normality. Most data sets were normally distributed, but some - notably those for flatness - were not, thus were transformed to \(\log_{10}\); transformed data were accepted as normal (p < 0.05) (Jones, 1969).

Clast size and shape variation among and along transects was analyzed with one-way analysis of variance (ANOVA), but as this does not indicate where significant differences, if any, lie, multiple t tests were also used to con-
SLOPE MORPHOMETRY

The transects were 250 to 530 m long, and covered an altitudinal span of 125 to 235 m. All were bounded at their apex by rockwalls, but these differed widely in size. The east transects (A, B), below the massive collapsed dome, had cliffs > 100 m tall (Fig. 3) while the west profiles (C, D) were below small isolated dome remnants only 18 to 25 m tall. Profiles A, B, and C merged gradually with debris-avalanche deposits at the talus foot, but D ended in a sizable depression > 120 m wide and 25 m deep partially filled by meltwater (Crags Lake, Fig. 1). Early in the season this lake - actually a pond - occupies most of the depression, but quickly shrinks during the hot summer days, and usually dries and disappears by late July or August.

Slope angle increased steadily upwards along the four sections, reaching a maximum value below the dacite walls; maximum gradient dropped gradually from transects A to D (Fig. 4). All sections showed similar shapes: a predominantly rectilinear talus throughout most of the transect, and a well-developed concavity at the basal slope. Concavity indices were high, with similar correlation coefficients (r) for profiles A, B, and C, and highest along D (Table I). The first three transects showed a slightly abrupt break near the base, where angle dropped in a short distance from ≥ 20° to ≤ 7°. This break could not be discerned along section D, since its lower 15-25 m were covered by Crags Lake. This basal segment is also affected by lacustrine processes, such as wave activity, basal sapping, etc., around the receding margins of the pond, as attested by minute shoreline steps which gradually appear during the summer drought. The nearly total lack of vegetation on a horizontal belt directly above the pond also suggests that this depression remains filled with snow and / or water during most of the year.

TABLE I

<table>
<thead>
<tr>
<th>Transect</th>
<th>Aspect</th>
<th>Length (m)</th>
<th>Maximum Inclination</th>
<th>Concavity Index(*)</th>
<th>Rockwall Height (m)</th>
</tr>
</thead>
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<tr>
<td>A</td>
<td>262°</td>
<td>490</td>
<td>37.5°</td>
<td>0.939</td>
<td>-120</td>
</tr>
<tr>
<td>B</td>
<td>285°</td>
<td>500</td>
<td>37.4°</td>
<td>0.936</td>
<td>-145</td>
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<tr>
<td>C</td>
<td>313°</td>
<td>530</td>
<td>36.8°</td>
<td>0.937</td>
<td>20 · 25</td>
</tr>
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<td>250</td>
<td>35.3°</td>
<td>0.974</td>
<td>18 · 20</td>
</tr>
</tbody>
</table>

(*) : Correlation coefficients (r) of regressions between log-transformed distance along the talus and slope angle; all regressions significant at p < 0.001 level.

In addition to these contrasts among profiles, clast size and talus texture showed pronounced variation within transects: size of clasts and the percentage of the slope surface they occupied (thus also the WAPS) increased toward the basal talus. Gravel cover was always much higher near the base.
FIGURE 4. Longitudinal profiles of the talus. Slope angle values shown are averages of 5 measurements taken at transect stations, and correspond to 50-meter long sections. All graphs are oriented from SE-SSE (left) to NW-NNW (right); see Fig. 1 for transect location. Transect D shows the level of Crags Lake at the time of profile survey (Aug. 16, 1991). Blank labelled arrowheads indicate location of sampling stations for particle morphology and texture. Shaded outlines show approximate extent of the dacite outcrops above the talus. Elevations along the left margin of sections are in meters; drawings do not show any vertical exaggeration.

FIGURE 5. East side of the Chaos talus, near transect A. Note the large blocks covering the talus nearly to its apex; light zones below cliffs are occupied by finer debris. The dark circular patches on boulders are prostrate shrubs of rock spirea (Holodiscus microphyllus). Shrubs have diameters ranging from ~1.3 to 2.8 m (large, darker shrub on lower talus). July 1991.

Versant est du talus du Chaos, près du transect A. À noter les gros blocs qui jonchent le talus près de son point le plus élevé ; des débris plus fins recouvrent les parties claires sous l’escarpement. Les taches sombres circulaires sur les blocs sont des formes prostrées d’arbisseaux (Holodiscus microphyllus) dont les diamètres varient entre ~1,3 et 2,8 m (à la partie inférieure du talus). Juillet 1991.
the talus apex than at the footslope, but gravel increment along transects was not gradual. Tests showed that a sharp rise in gravel cover produced two significantly different (p < 0.001) sets of plots [plot N is in brackets] along transects B ([1-7] vs [8]), C ([1-3] vs [4-8]), and D ([1] vs [2-5]) (Table II). Gravel rise upslope transect A was similar but spottier; a main texture break was detected above plot 4, and another one below plot 7 (see Table II).

Axial clast length showed a complex variance. Maximum mean clast size and WAPS were found on basal plots - except on B, but the drop in a-axis length was more abrupt along transects such as C, where size range was greatest (Fig. 7). Clast size dropped steadily toward the talus apex along all transects except B, where the lower-middle slope had the smallest particles; a ‘reversed’ sorting was found above this area (Table III). DMR, F, and t tests show that on all profiles clast size variance results in homogeneous groups of basal-talus plots (one plot for A, C, and D; two plots for B) which are significantly different (all at p < 0.001) from those found immediately above them. Tests suggest the presence of three or four such discrete groups along each transect, which show no overlap except on transect B, where upper-talus plots are not statistically different from those at the footslope (Fig. 7). The results show that, for the chosen sampling interval (50 m), changes in clast size occur swiftly along the talus; however, a shorter interval might perhaps reveal more gradual changes.

Clasts were ‘very well to well sorted’ (Folk, 1980) on all sampling plots, as their sorting index (Ø S.D.) was between ~0.28 and 0.5 Ø (Fig. 8). Degree of clast sorting on plots showed no clear trends along slopes, but slightly greater indices (i.e., less pronounced sorting) were seen both on basal-talus and talus-apex plots. This simply means that primarily large particles (on the former), or small (on the latter), lie next to distinctly smaller or larger debris, respectively.

THE VARIATION OF CLAST SHAPE

Clast shape variation along transects A and B was more gradual, and showed a less clear spatial pattern, than that observed for size. On both profiles, sphericity increased toward the slope base, elongation and flatness toward its apex (all ANOVAs are significant at p < 0.001) (Table III).
Flatness ratios showed a high inverse correlation ($r^2 = 0.944$ on A, 0.95 on B; both at $p < 0.001$) with sphericity indices (Goudie, 1981). All tests indicated that clast shape changes were somewhat more pronounced either at the talus top or its base, but overall shape variance was gradual. DMR and F tests identified several discrete plot groups (two to five, depending on transect or shape parameter) with statistically similar plots ($p < 0.001$), but which partially overlapped with other such groupings along the slope. In other words, important changes in clast shape do take place along both transects, and the upper- and lower-most plots there differ significantly from each other ($p < 0.001$) (Table III), but, in contrast to size variance, shape changes occur incrementally, thus no distinct zones or sharp breaks are detected on the talus.

Clast shape data were combined in four sets of two plots each according to relative slope position - upper (U), upper middle (UM), lower middle (LM), lower (L) (Pérez, 1989) - and plotted on ternary diagrams to assess the progressive sorting of fragments visually by shape (Fig. 9). The diagrams, each based on 100 clasts, show that these become gradually more compact (clustered on the upper corner of the triangle) downslope; this seems a bit more pronounced along transect B. KS tests comparing the percentage of all compact clasts (C, CP, CB, and CE in Fig. 9) (McSaveney, 1971) verified this, as well as the subtle nature of shape variance. On transect B, clasts on the L and LM slopes are similar, and significantly more compact ($p < 0.001$) than those on the UM and U slope, which form another distinct group. Along transect A, particles on the L, LM, and UM slopes are comparably equidimensional, but all differ ($p < 0.025$) from the clasts on the U slope, which are significantly less compact. These data suggest that larger clasts may be somewhat more spherical than smaller fragments.

Regression also indicated that, as clasts increase in size downslope, they also become less elongated and flattened, and attain a greater sphericity, but these relations between size and shape were not strong. Correlation coefficients ($r$) between nominal clast diameter and shape parameters were low, but all were higher along section A (flatness: -0.344, sphericity: 0.321, elongation: -0.237; all significant at $p < 0.001$) than along B (flatness: -0.123, sphericity:0.118, elongation: -0.107; significant at $p < 0.05$). The greater association of size and shape on the first profile seems related to
TABLE III

Clast morphology along transects A and B. Sampling transects start at the basal talus. Data indicate averages of 50 measurements at each sampling plot

<table>
<thead>
<tr>
<th>Plot</th>
<th>Nominal Diameter (cm, $\phi$)</th>
<th>Sorting (O, S.D.)</th>
<th>Elongation Index (*)</th>
<th>Sphericity Index (*)</th>
<th>Flatness Ratio (*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>45.3, -8.77</td>
<td>0.393</td>
<td>1.454</td>
<td>0.733</td>
<td>1.661</td>
</tr>
<tr>
<td>2</td>
<td>35.9, -8.44</td>
<td>0.382</td>
<td>1.541</td>
<td>0.709</td>
<td>1.782</td>
</tr>
<tr>
<td>3</td>
<td>34.3, -8.38</td>
<td>0.349</td>
<td>1.482</td>
<td>0.728</td>
<td>1.666</td>
</tr>
<tr>
<td>4</td>
<td>25.3, -7.96</td>
<td>0.29</td>
<td>1.533</td>
<td>0.675</td>
<td>1.919</td>
</tr>
<tr>
<td>5</td>
<td>26.6, -8.02</td>
<td>0.33</td>
<td>1.512</td>
<td>0.717</td>
<td>1.721</td>
</tr>
<tr>
<td>6</td>
<td>27.5, -8.07</td>
<td>0.321</td>
<td>1.529</td>
<td>0.704</td>
<td>1.785</td>
</tr>
<tr>
<td>7</td>
<td>19.3, -7.57</td>
<td>0.275</td>
<td>1.598</td>
<td>0.672</td>
<td>1.914</td>
</tr>
<tr>
<td>8</td>
<td>18.1, -7.47</td>
<td>0.28</td>
<td>1.595</td>
<td>0.649</td>
<td>2.105</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>32.2, -8.26</td>
<td>0.441</td>
<td>1.420</td>
<td>0.714</td>
<td>1.768</td>
</tr>
<tr>
<td>2</td>
<td>33.4, -8.32</td>
<td>0.433</td>
<td>1.399</td>
<td>0.730</td>
<td>1.715</td>
</tr>
<tr>
<td>3</td>
<td>22.5, -7.78</td>
<td>0.307</td>
<td>1.411</td>
<td>0.759</td>
<td>1.568</td>
</tr>
<tr>
<td>4</td>
<td>20.4, -7.62</td>
<td>0.368</td>
<td>1.418</td>
<td>0.719</td>
<td>1.735</td>
</tr>
<tr>
<td>5</td>
<td>21.3, -7.68</td>
<td>0.383</td>
<td>1.491</td>
<td>0.678</td>
<td>1.921</td>
</tr>
<tr>
<td>6</td>
<td>24.2, -7.88</td>
<td>0.347</td>
<td>1.565</td>
<td>0.693</td>
<td>1.852</td>
</tr>
<tr>
<td>7</td>
<td>24.0, -7.84</td>
<td>0.427</td>
<td>1.538</td>
<td>0.657</td>
<td>1.976</td>
</tr>
</tbody>
</table>
| 8    | 26.6, -7.98                   | 0.45              | 1.617                | 0.609               | 2.368             

(*): One-way ANOVA, Duncan’s Multiple Range and Scheffe’s F test indicate significant differences ($p < 0.001$) exist on both transects between the lowermost and uppermost plots. See text for further details.

FIGURE 9. Contoured clast-shape diagrams (after Folk, 1980; Pérez, 1987) for four relative slope positions along transects A and B. Each diagram is based on 100 clasts (two sampling plots combined). Key for slope position: U = upper, UM = upper middle, LM = lower middle, L = Lower. Clast density is indicated by shades. Shape classes: C = compact, CP = compact platy, CB = compact bladed, CE = compact elongate, P = platy, B = bladed, E = elongate, VP = very platy, VB = very bladed, VE = very elongate.


FIGURE 8. View of the upper middle talus in an area covered by well-sorted, 8 to 12 cm-long blocks and cobbles. Scale is in dm (long shaded bars) and in cm. August 1991.

Vue du talus dans sa partie moyenne supérieure recouverte par des blocs et des galets de 8 à 12 cm de long bien triés (échelle en dm et cm). Août 1991.
the continuous rise in clast size down the talus (Fig. 7A),
while the more erratic size variation found on transect B (Fig.
7B) probably resulted in a weaker correlation. Regressions
between the axes of 100 clasts (Gardner, 1972; Pérez,
1986) also indicated similar relationships between particle
size and shape attributes, but were much less discriminating
than the tests above to indicate any relevant spatial associa-
tions.

CLAST FABRIC

Particle fabric data were also combined in four sets of two
plots each, which correspond to the relative slope positions
(U, UM, LM, L) above. As fabric diagrams and statistics are
based on data sets of 100 clasts, they are likely to show
more clearly defined orientations than those for the eight
individual sample plots - which contain only 50 points each -
(Stauffer, 1966). Fabric trends were similar along the two
sections (Fig. 10). Fabrics on the upper talus half (U+UM)
have a well-defined subhorizontal girdle which coincides with
the local slope; the principal mode, with a axis densities of 6-
10 %, is superimposed on this girdle and parallel to the slope
direction. Many clasts dip downtalus and plunge slightly less
than the slope plane, thus exhibit an upslope imbrication.
Overall, these fabrics show that most particles lie on the high
talus with their long axes roughly parallel to the talus surface
and slope line. Some noticeable fabric changes occur on the
lower talus. The slope girdle becomes less continuous and
pronounced, and main axial modes switch to an oblique
position on the LM zone. This is even more pronounced on
the L segment of A, where the main modes are nearly per-
pendicular to the slope; in addition, many particle axes are
randomly scattered throughout the diagram, pointing in all
directions. On the basal B talus, a dense main mode has
migrated to the diagram center, indicating that the bulk of the
clasts plunge steeply into the slope plane.

Fabrics were analyzed following a sequence of statistical
procedures described in detail by Steinmetz (1962); this vec-
torial method allows a three-dimensional analysis of clast
attitude, as data for both the azimuthal orientation and the
dip of the a axes are combined. In addition, clast alignment
was studied with the Vector Magnitude (L %) (Curray,
1956), a two-dimensional method restricted to azimuthal data which
provides some measure of the strength of preferred particle
orientation. It must be noted that this procedure does not
analyze true clast fabrics, and it is therefore more appropri-
ate for the analysis of basically 'planar' features such as soil-
or sorted stone-stripes (Hall, 1979; Pérez, 1984, 1992) with
an inclination concordant to that of the substrate. However,
due to its simplicity, the method has been widely used.
Consequently, the results of this report can be easily compared
with those of other studies (Bertran et al., 1997).

Following Steinmetz (1962), resultant vectors were
obtained by rotation of axial orientations to the (0°-180°)
hemisphere; thus, data show angular differences between
the mean vector and (down)slope direction. Resultant vector
directions become progressively more oblique on both pro-
files toward the basal talus, where vector dip also attains a
greater angular difference with the talus plane (Table IV).
The imbrication index (percentage of clast axes that plunge

FIGURE 10. Clast fabric for relative slope positions along transects
A and B. Each diagram is based on 100 clasts (two sampling plots
combined). Key for slope position as in Figure 9. Contoured Schmidt
stereonets were projected on the lower hemisphere; shades indicate
the density of projections of the long particle axes (see graphic
scale). The intercept of the slope plane is shown by the great circles.
Slope direction (indicated by a dark arrowhead) is towards bottom of
page; true north is shown by an empty arrowhead

Orientation des fragments selon l'emplacement relatif le long des
transects A et B. Chacun des diagrammes s'appuie sur 100
fragments (combinaison de deux relevés). Voir la légende de
l'emplacement à la figure 9. Stéréogrammes de Schmidt
(hémisphère inférieure) sur lesquels les trames reflètent la densité
des projections des grands axes des particules. Le grand arc de
cercle représente l'inclinaison du versant. La direction de la pente
(vers le bas) est donnée par la flèche tramée ; la flèche non tramée
indique le nord géographique.
less than the slope plane) (Albjär et al., 1979) also drops steadily down talus. KS tests showed that within-transect imbrication differences are significant (p < 0.001) only between the U and the L populations, but detected no between-transect differences when plots at the same relative slope position were compared. A test for randomness of orientation (Watson, 1956) showed all clast populations were significantly oriented (p < 0.01); however, greater vector orientation (Watson, 1956) showed all clast populations were significantly oriented (p < 0.001) along transect A indicate that rockfall activity, dry debris slides, snow-related processes (including snow avalanches), and debris- and mud-flows are the most significant agents of debris transport on the Chaos Crags.

Following Curray (1956), no distinction was made between opposite ends of the particles; analysis of L % values was made only in a range of 180° after axial rotation to one hemisphere. Vector magnitude was computed after doubling the angles of azimuthal data (Doornkamp and King, 1971: 346); this is needed in order to obtain a non-symmetric periodic distribution which reflects the true central tendency of data sets (Krumbein, 1939; Curray, 1956).

Vector magnitude showed gradually increasing values upslope on both transects (Table IV). Maximum L values (~45 %) were similar along both profiles; the downslope drop in L % was more pronounced on B, where the lowest L (19.5 %) was found. Comparable spatial trends were recently reported (Bertran et al., 1997: table 1) along talus slopes in SW France. Vector magnitudes were analyzed with the Rayleigh test (Curray, 1956: fig. 4); this indicated that all data sets, except the lowest plot on transect B, were significantly oriented (p < 0.001). The L % data confirm the findings of the three-dimensional vectorial analyses: clast orientations along both transects become increasingly stronger as the talus apex is approached.

FIELD OBSERVATIONS OF PROCESS ACTIVITY

The talus at Chaos Crags is presently affected by different processes. Observations of specific geomorphic events, and of deposits and other kinds of evidence of their activity, indicate that rockfall activity, dry debris slides, snow-related processes (including snow avalanches), and debris- and mud-flows are the most significant agents of debris transport on the Chaos Crags.

### TABLE IV

Clast fabric statistics according to relative slope position. Each slope position includes data from two consecutive sampling plots (= total of 100 particles). Sampling transects start at the basal talus.

<table>
<thead>
<tr>
<th>Slope Position</th>
<th>Angular Difference (1)</th>
<th>Resultant Vector</th>
<th>Angular Difference (2)</th>
<th>Imbrication Index (%)</th>
<th>Vector Strength (R)</th>
<th>Diameter, Cone of Confidence (°)</th>
<th>K (Precision Parameter)</th>
<th>L % (Vector Magnitude)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transect A:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>62.3°</td>
<td>30.3°</td>
<td>+11.3°</td>
<td>22</td>
<td>73.28</td>
<td>26.4°</td>
<td>3.71</td>
<td>32.33 a</td>
</tr>
<tr>
<td>LM</td>
<td>61.8°</td>
<td>28.3°</td>
<td>-3.4°</td>
<td>38</td>
<td>72.31</td>
<td>27.0°</td>
<td>3.58</td>
<td>35.42 a</td>
</tr>
<tr>
<td>UM</td>
<td>52.9°</td>
<td>35.0°</td>
<td>+1.8°</td>
<td>41</td>
<td>73.38</td>
<td>26.3°</td>
<td>3.72</td>
<td>36.19 a</td>
</tr>
<tr>
<td>U</td>
<td>50.9°</td>
<td>27.3°</td>
<td>-6.2°</td>
<td>51</td>
<td>81.27</td>
<td>20.9°</td>
<td>5.29</td>
<td>45.43 a</td>
</tr>
<tr>
<td>Transect B:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>76.8°</td>
<td>34.9°</td>
<td>+12.6°</td>
<td>29</td>
<td>64.22</td>
<td>32.6°</td>
<td>2.77</td>
<td>19.46 b</td>
</tr>
<tr>
<td>LM</td>
<td>59.8°</td>
<td>34.1°</td>
<td>+2.3°</td>
<td>42</td>
<td>71.00</td>
<td>27.9°</td>
<td>3.41</td>
<td>27.32 a</td>
</tr>
<tr>
<td>UM</td>
<td>55.1°</td>
<td>33.8°</td>
<td>+0.4°</td>
<td>40</td>
<td>68.09</td>
<td>29.9°</td>
<td>3.1</td>
<td>37.34 a</td>
</tr>
<tr>
<td>U</td>
<td>49.2°</td>
<td>28.5°</td>
<td>-3.5°</td>
<td>56</td>
<td>78.71</td>
<td>22.7°</td>
<td>4.65</td>
<td>44.7 a</td>
</tr>
</tbody>
</table>

(*) : All values are significant at p < 0.001 level. Rayleigh test for L %: (°): p < 0.001; (†): p < 0.05.

Key for slope positions: L = Lower; LM = Lower Middle; UM = Upper Middle; U = Upper.

All data refer to Steinmetz (1962) vectorial analysis, except L %, which is the ‘vector magnitude’ of Curray (1956). Key: Angular difference (1): [Slope direction] minus [resultant vector azimuth]. Angular difference (2): [Slope inclination] minus [resultant vector dip]. Superscript letters refer to the significance levels of a Rayleigh test for L % values.
ROCKFALL ACTIVITY

The general aspect of the study site, coupled with its intensely fractured bedrock, provides an ideal setting for rockfall activity, especially during summer. A northern exposure allows much snow to persist on the Chaos Crags well into the warm season; this provides an ample supply of moisture to the rockwalls. In addition, the north face experiences broad daily temperature fluctuations, which greatly affect rockfall occurrence (Gardner, 1983).

Examination along the cliff bases showed highly fractured, brecciated dacite, with no lichen or vascular plant cover. Sizable fresh-looking, lighter-colored patches, presumed to be areas of recent rockfall activity, were evident on the rockwall face, notably above transect B. Some small impact craters and aligned bump holes (Rapp, 1960b) on the upper talus also indicated areas of recent rockfall. Actual rockfall events were witnessed on numerous occasions. However - and despite some initial apprehension about spending much time below the 'unstable' cliffs of the Crags - rockfall events were not very spectacular. Most rockfalls were small, removing only a few cubic meters of material; many events took place directly above couloir areas incised along the base of rockwalls (Fig. 3). Nearby events were easily noticed by the noise of falling debris; distant events were often evident by sizable dust clouds caused by falls (Clark et al., 1972) or by large bouncing blocks that continued down the talus. Rockfalls had a tendency to cluster about mid-day hours; most events observed took place between noon and 3 p.m., when rock-wall temperatures peak in their diurnal cycle (cf. Gardner, 1983). Rockfalls were often tightly time-clustered, several events occurring within minutes in the same cliff area, even under clear skies. This may happen because, following an initial rockfall, the change in stability on the cliff face provides a greater chance for other rockfalls to occur (Luckman, 1976).

Most rockfall debris were transported only a short distance and remained on the U or UM talus after rolling and sliding on its surface; however, large boulders normally separated from moving debris masses and continued to the footslope. On one such event, a block ~110 cm long (later located) detached from the falling mass and quickly bounced downhill > 450 m to the basal talus. Some rockfalls must occur on snow-covered talus; this may affect the distance of debris travel. As noted above, a hard snow crust allows debris descent to the footslope, but soft snow (i.e., in winter) could mire even large blocks, which may remain on the high talus following snow melt. Such an event seems to have taken place during the 1990-91 season, when a sizable rockfall produced a fresh scar area 6-10 m² on the cliff above transect C; many massive blocks and much fine debris from the event were left on the upper talus, 20-30 m below the rockwall base.

Many rolling and bouncing blocks must reach the footslope; ample evidence for rockfall impact is found in talus vegetation. Forty plant species (5 trees, 6 shrubs, 25 herbs, and 4 graminoids) grew on the talus, but only plants showing relevant geomorphic interactions will be mentioned here. Infrequency, stems in some plants, such as Eriogonum spp. or Holodiscus microphyllus, had been scarred and/or crushed by falling rocks. Scrape marks and impact scars (Hétu, 1990) were more common on the trunks of trees, which have invaded a sizable area on the west basal talus (Fig. 11). Many trees had wounds on the upslope side of their stems or branches; these were usually 10-50 cm above the ground surface, although some scrapes reached 110 cm height. Most scars were superficial, only bark having been removed, but in some trees several cm of wood had also been eroded; a WW pine on the basal talus (near transect B) had lost bark and wood around 50 % of its girdle from 70 to 210 cm height, and the tree was severely tilted. Another pine on the basal talus (transect D), had an unusual wound: a dacite block (11 x 8 cm) had hit the tree stem and become firmly embedded in it 150 cm above the base (Fig. 12). Most of this damage seems to have been caused by bouncing blocks, but some may also have resulted from snow avalanches (see discussion below).
observed on gravel / pebble areas from ~29° to 34°, which seems to be the steepest gradient reached by fine debris on the Chaos talus. An unusually well-developed sieve effect was found in block areas of the UM and LM zones downslope from the finer upper talus (cf. Hétu, 1995). Excavation showed only the upper 30 to 50 cm of the block deposits to be ‘open-sieve’, while small pebbles, cobbles, and gravel uniformly filled all interstices below this depth; this supports the idea that frequent grain flows initiated on the slopes above gradually bring fine sediment to the blockier areas. B. Hétu (pers. comm., 1997) has also observed this process in the Pyrénées.

It should be emphasized that dry sliding was quite pronounced on the steep upper segments of the Crags talus. In some places, extensive sliding occurred constantly as I walked across the slope; I believe that, of all the talus slopes I have visited over the past 18 years, the one at Chaos Crags is the most unstable as regards grain flows. The morphology of dry debris slides was similar to that observed elsewhere (Francou and Hétu, 1989; Bertran et al., 1997). Sliding took place along narrow elongated tongues parallel to the slope. Streaming zones had variable size; the smaller events affected strips 1-3 m long, 40-50 cm wide, and a surficial debris layer 10-15 cm thick. The largest debris slides involved zones 12-14 m long, 3-5 m wide, and 20-40 cm thick. Grain flows occurred as a shallow debris layer moved slowly at first, and then accelerated to about 10-12 m min⁻¹; thus, most events were over in < 1 min.

Sliding motion was ‘layered’, with the upper layer slipping fastest (Matveev, 1963; Hétu et al., 1995). Larger cobbles and blocks remained at the surface while moving quickly over a mass of finer pebbles and gravel; these last actually migrate to, and become concentrated at, the base of the grain flow due to ‘kinematic sieving’ (Van Steijn et al., 1995). Spherical clasts rolled and bounced swiftly, like marbles. Slab-shaped fragments slid with their ab plane parallel to the slope surface, while the a axis of elongated particles remained parallel to the slope during descent. Coarser clasts were laterally segregated to form narrow levees, and / or travelled to the base of the sliding mass, where piling up of debris built small bulging lobes (Van Steijn et al., 1995; Bertran et al., 1997). Some larger and more spherical blocks continued rolling beyond the slide to the talus base (Rapp, 1960b) causing small dry ‘impact avalanches’ (Pérez, 1985) on their way down. Small slip faces often remained at the upslope (detachment) end of grain flows; along with the basal lobes, these produced a characteristic profile of stair-shaped terraces (Gerber and Scheidegger, 1966). Grain-flow deposits were recognizable as elongated zones with a finer veneer than the surrounding slope (Fig. 13). This is due in part to the quick lateral / frontal segregation of coarser blocks during motion, but also indicates that the surface over which the grain flow stops has already been affected by sieving of fine grains for some time (P. Bertran, pers. comm., 1997).

Presence of isolated blocks also caused a stepped topography, as stable boulders (blocs freineurs, Francou, 1986) firmly embedded in the talus obstructed the flow of finer debris, which piled above the rocks. Debris damming generated distinct elongated ‘cobble stripes’ (Pérez, 1988c) and enormous fine-debris bulges upslope from blocks. Lateral deflection of sliding debris toward the boulder edges also created narrow, elongated cobble / pebble tongues extending downslope at either side from the blocks (Pérez, 1993). Dislodging of boulders caused sizable slides. While sampling the upper talus near the cliffs, an accidentally loosened, 90 cm-long block began creeping; this destabilized a debris wedge 2.5-3 m wide, 13-14 m long, and 30-50 cm thick, above the block. The debris mass slipped as a unit 6-7 m before stopping, although the largest clasts kept bouncing to the footslope. Elongated debris tongues also formed upslope from plants of all sizes. Small shrubs and compact cushion plants such as prickly phlox (Leptodactylon pungens), coyote mint (Monardella odoratissima) or phacelia (Phacelia trigida) dammed wedge-shaped debris tails 30-70 cm long and 10-20 cm thick. Larger shrubs of rock spirea (Holodiscus microphyllus) were often nearly buried by enormous piles of rubble. The trunks of many trees also detained

FIGURE 12. Upslope side of the trunk of a western white pine growing on the basal talus near transect D. The 25-cm thick trunk has been hit by a bouncing dacite block (11 x 8 cm). Bark has grown around the block, now firmly embedded in the stem at a ~150 cm height. July 1992.
moving debris, and lateral deflection around stems produced clast tongues similar to those near blocks. Like debris, organic litter is also affected by sliding, its overall distribution patterns following those of moving debris; e.g., litter piling produced O horizons 90-170% thicker upslope from tree stems than downslope (F.L. Pérez, unpubl. data).

Several additional plant characteristics, including their spatial patterns, indicate the severity of dry sliding. Most plants in fine-debris areas grow below boulder dams, as these provide stable shelters against constant talus sliding and burial by moving debris (Pérez, 1994). Rock spirea was particularly common in this type of habitat, where shrub edges sharply coincided with those of boulders, indicating that branches are continuously 'trimmed' by downstreaming debris on both sides of the rock. As a result of this lateral sliding, many small mat-forming plants (Arenaria kingii, Penstemon davidsonii) growing on unstable talus areas also attain a clearly downslope-elongated shape, and on one occasion, a line of four small clones - probably part of the same 'individual' - of rock spirea extended 3.5 m below a large boulder shelter.

In addition to these surface features, the roots of most plants indicate that dry grain flows affect them substantially. Excavation of many plant specimens of 30 species common on the taluses of Chaos Crags and other LVNP mountains shows that, invariably, the taproots and buried stems of plants on fine debris areas 'trail' upslope, with 80-100% of all root biomass located above (Pérez, unpubl. data). This is a common pattern in talus plants (Pérez, 1991a), and is usually ascribed to "...periodic burial by [sliding of] upslope material." (Kershaw and Gardner, 1986: 226). Other root features, such as pronounced layering (formation of new root layers or clusters along buried stems) observed in many specimens of rock spirea and silverleaf lupine also attest to the prevalence of dry sliding on the fine gravelly areas inhabited by these plants.

**TRANSPORTATION OF DEBRIS BY SNOW-INDUCED PROCESSES**

Because the talus was visited only during summer, no snow avalanches were ever observed, but field evidence indicates that these events play a role in debris transport. Perched blocks (Ward, 1985) were common on the basal east talus, but not on the west end, showing that avalanches occur more frequently below the dacite rockwalls. The greater density of trees on the west side (Fig. 11) would also indicate a lower avalanche frequency there. Several broken tree stumps and severed trunks (2-6 m long and ≤ 35 cm diameter) were found on the footslope; they were missing from the western tip of the site, but became more common in an eastward direction. Tree stumps showed jagged irregular breaks at 30-95 cm height, and were between 21 and 36 cm diameter. This suggests that seedlings and saplings are flexible enough to bend and avoid destruction, but as they grow beyond a critical size they have a greater chance of being killed by snow avalanches. Stumps found were of either WW pine (Pinus monticola) or California red fir (Abies magnifica). The first may be more frequently destroyed because it is an efficient talus colonizer (most common tree on the slope). Although there were few specimens of red fir, this tree has brittle wood, thus breaks easily and suffers from 'frequent falls' (Munz and Keck, 1970: 50). Many affected trees had survived and produced a dense basal growth by suckering around the severed trunk or layering of surviving branches (Fig.14). Large clonal groups seemed to have produced several generations of upright stems that were broken by successive avalanches.

A fortuitous event illustrates the importance of snow avalanches. During coring in 1992 trees were flagged for identification purposes; in 1993, I could not relocate a WW pine (Pinus monticola) or California red fir (Abies magnifica). The first may be more frequently destroyed because it is an efficient talus colonizer (most common tree on the slope). Although there were few specimens of red fir, this tree has brittle wood, thus breaks easily and suffers from ‘frequent falls’ (Munz and Keck, 1970: 50). Many affected trees had survived and produced a dense basal growth by suckering around the severed trunk or layering of surviving branches (Fig.14). Large clonal groups seemed to have produced several generations of upright stems that were broken by successive avalanches.
Debris flows were never observed in progress, but their dry tracks, levees, and terminal fans were common on fine-debris areas, especially on the upper slope and on the west end of the talus (Fig. 15). Most debris-flow tracks were short (a few meters long) and restricted to gravel / pebble zones near the talus apex; observations on Lassen Peak (Pérez, 1989) indicate that many flows originate below snowbanks by rapid melting during spring, but rainstorms probably cause some as well. Meltwater also produces much runoff, even if just for short distances; part of the fine matrix in between talus blocks may have been transported by running water. Many debris flows start in the couloirs along the rockwall base due to ample snow accumulation and fine-debris availability (Fig. 3). An extensive area on the UM segment of transect C had been affected by sizable debris flows, which had incised the talus with long, narrow (1-2 m) tracks. Channels had been filled later with pebbles/cobbles, forming networks of long ‘rock streams’ (McSaveney, 1971; Pérez, 1986) coarser than the flanking levees, with a finer gravel / pebble texture. In the Andes (Pérez, 1991b), clasts are heaved from levees by needle ice, then settle mainly in the tracks to form these peculiar rock streams, but clast sorting on the Chaos talus may be primarily gravitational. Cobble streams - especially steeper, longer ones - were very unstable and easily set in motion by dry sliding (cf. Matveev, 1986) thus allowing for a quick clast transfer to lower slope areas.

Although most debris-flow activity occurs high on the talus, some large events reach the basal slope. During the 1990-91 season, a huge debris flow originating in a couloir at the cliff base travelled > 400 m to the footslope, where a large terminal fan 30-40 m wide and 1.5-2 m thick was built (Fig. 15). This fan, like the flow tracks, was composed of fine gravel heavily armored with large blocks and cobbles buoyed up by the fluid mass. Many older, eroded tracks are still evident throughout the west talus, indicating that sizable events are not uncommon.

Additional agents of debris movement on the Chaos talus might include disturbance by needle ice and other types of frost. Needle ice may cause much debris transport on fine talus (Pérez, 1985, 1993; Francou, 1986) and I have often observed signs of its activity (soil nubbins, striated soil, stone gaps) on the slopes of Lassen Peak (Pérez, 1988a, 1989, 1990a). Debris could be gradually transferred to tree branches as the snow cover melts; height of deposition on a tree may indicate snow depth at the time of the deposition event. Gliding over snow could also have produced some of the ‘perched’ blocks noted above (see discussion below). Hétu (1989, 1990) reported on the multiple roles of snow on talus slopes in Québec, including that of rapid snow creep, but the lack of push ridges or other relevant features on the Chaos talus argues against the effectiveness of this and similar snow-induced processes.

DEBRIS- AND MUD-FLOWS, AND ADDITIONAL PROCESSES OF DEBRIS TRANSPORT

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the slope, related to the height of cliffs above the talus (cf. role for debris flows. active there, the concavity may be ascribed to debris flows. but as field evidence suggests the first process was not very explosion. The high concavity attained by transect D could shape of the underlying surface created during the volcanic these authors (33° took place at a lower angle (~20°) than that reported by... MORPHOMETRIC DATA AND PROFILES (Table I, Fig. 4) show all... talus sections were bisegmented and had a strong basal concavity (Francou and Manté, 1990). There was a sharp... particle homogeneity when in reality debris at depth are... vector magnitude (L %) values on the Chaos slope were... talus slope was about 40 m wide. Several smaller, older, and partially eroded debris-flow tracks appear also on the upper right side of the photograph, taken August 1991 between transects C and D.

Dépôts de glissement récents sur talus à texture fine. La grande trace de glissement et son cône terminal ont été formés au cours du printemps (?) de 1991. La largeur du cône est d'environ 40 m. Plusieurs autres plus petits glissements, plus anciens et partiellement érodés, apparaissent au côté droit supérieur (photographie prise en août 1991, entre les transects C et D).

(Meentemeyer and Zippin, 1981; Pérez, 1984). It must therefore be concluded that the recent soils on the Chaos talus are simply too coarse to produce needle-ice growth.

INTEGRATION OF RESULTS AND OBSERVATIONS

Morphometric data and profiles (Table I, Fig. 4) show all talus sections were bisegmented and had a strong basal concavity (Francou and Manté, 1990). There was a sharp reduction in gradient and a change in slope form from rectilinear to concave near the footslope, but this slope break took place at a lower angle (~20°) than that reported by these authors (33°). This inflection might simply reflect the shape of the underlying surface created during the volcanic explosion. The high concavity attained by transect D could indicate either significant avalanche or debris-flow activity, but as field evidence suggests the first process was not very active there, the concavity may be ascribed to debris flows. The complex micro-topography of old channels, levees, and lobes on this basal talus (Fig. 15) also suggests an important role for debris flows.

There was a noticeable gradient in particle size across the slope, related to the height of cliffs above the talus (cf. Pérez, 1989); the larger and more abundant clasts found below rockwalls suggest that present debris supply exerts an important control on talus morphology.

The pronounced within-talus variation in surficial talus texture, clast size and fabric, and the field observations on geomorphic activity indicate a strong stratification of dominant processes of debris transport along the slope. The upper talus, with few and small clasts scattered over fine gravel, is affected mainly by dry grain flows, which allow particles to creep and slide downhill with their a axes roughly parallel to the slope plane and direction (cf. Van Steijn et al., 1995), as this alignment offers the least frictional resistance (Statham, 1973). Creeping clasts develop an imbricate arrangement as they stop against other particles on the slope (Albjäär et al., 1979). The strong imbrication observed also indicates the significance of dry sliding. In contrast, the large blocks which cover the lower talus are mainly deposited by rockfall. Big stones, while rolling and bouncing, tend to rotate about their long axes, which become aligned with the contours (Caine, 1987) (Fig. 10A-L); but after colliding with other blocks on the talus, this orientation may not be preserved, and most clasts attain an isotropic fabric (Fig. 10B-L). These processes also effect a normal downslope size sorting. The weaker shape sorting found downtalus also conforms with the proposed process stratification. Compact, isometric blocks rotate easily when set in motion and reach the footslope, but platy / elongated particles move chiefly by creep, and friction normally arrests their descent well before they reach the talus base.

The reversed size sorting on upper transect B (Fig. 7B) is unusual, especially since it is under the tallest cliff zone. Clasts falling on this area should readily bounce downtalus if they landed on the bare slope. Perhaps rockfalls during winter, when the talus is covered by snow, have affected this zone recently in a manner similar to that described above for the rockfall event in 1990-91. This would allow sizable boulders to remain on the upper talus, but it is not apparent why the nearby transect A, also below tall cliffs, does not display a comparable sorting.

Within-plot sorting on talus is seldom discussed, and seems poorly understood. The low sorting indices found on most plots (Table II) suggest that fragments are efficiently segregated along the slope. This may result from frequent debris transportation, which should generate a better sorting (cf. Folk, 1980). In addition to rockfall, dry sliding seems particularly effective in causing sorting by nearly constant debris transfer down the talus. Surficial sorting is greatly affected also by the sieve effect, which gives the external appearance of particle homogeneity when in reality debris at depth are much more heterogeneous and unsorted.

Ample field evidence shows that snow avalanches occur on all but the western tip of the talus, where many large trees grow (Fig. 11). Field observations also indicate that debris flows frequently transport significant amounts of rubble on the west half of the slope (Fig. 15). The spatial segregation of debris flows and snow avalanches across the talus produces a ‘secondary’ gradient, which superimposed on the primary (rockfall / dry slides) trend down the slope generates a complex spatial pattern of geomorphic activity on the Chaos talus (Fig. 16).

Vector magnitude (L %) values on the Chaos slope were somewhat higher than those found on most taluses (Bertran et al., 1997: table 1), especially near the slope apex, where values as high as 44.7 and 45.4 were encountered (Table IV). Bertran et al. (1997: 2, 5) noted that on rockfall talus
activity and pattern. Tree dating at the Chaos talus suggests that living trees are an important source of evidence for geomorphics. Researchers have made little use of botanical indicators of process origin and recency of the Chaos talus might, somehow, make it uniquely different from other, much older taluses. However, the patterns of debris sorting, texture and fabric, as well as geomorphic activity, are similar to those of many talus slopes in the French Pyrénées, where dry grain flows played a significant role in slope evolution, and concluded that frequent, sizable sturzstroms normally deposit little or no material on the breakaway surface, which is "...for most of its area...swept clear of debris during the collapse". These studies, coupled with the absence of major distinctive features on the Chaos talus, suggest there is no compelling reason to accept the model of direct debris deposition by the VDAs of 1675, and that most of the talus deposits on the mountain scar were added after the collapse event.

The only striking - if not easily quantifiable - feature of the Chaos talus relates to the extreme instability of most of the slope, and to the inordinately high frequency of dry sliding events observed. Allen (1970: 348) noted that grain flows, although "...the dominant process shaping many screes...", will occur infrequently if sediment supply to the talus remains low, but with large deposition rates from rockwalls, such sliding becomes more continuous and affects larger portions of the talus. Hétu et al. (1995) studied a relict talus in the French Pyrénées, where dry grain flows played a significant role in slope evolution, and concluded that frequent, sizable dry sliding events could only have been maintained by constant delivery and renewal of debris supply at the talus apex. This may have resulted from either high rates of rock weathering, or the recurrent agency of some releasing event, probably seismic activity (B. Hétu, pers. comm., 1996). Occurrence of dry grain flows should also have been facilitated by the fact that the brecciated dacites of the Chaos cliffs tend to easily break down in small gravel to pebble-sized fragments (cf. Hétu et al., 1995).
The extreme sliding activity observed at the Chaos Crags suggests that either the present rates of (fine) debris supply to the upper slope remain unusually high, or that much of the sediment produced following the genesis event 325 years ago is still resting on the upper talus. Instances of similar rapidly-formed slopes are scarce in the literature. Clark et al. (1972) reported on the rapid growth of a talus cone in the Chugach Mountains (Alaska) following the great 1964 earthquake. During a 6-yr period, the weakened, unstable rock-walls supplied ~1.3 million m$^3$ of debris to a cone about 5 times smaller than the Chaos talus (area estimated from Fig. 1, Clark et al., 1972). Unfortunately, no follow-up studies seem to have been carried out, and it is not known if this talus continued growing at an accelerated pace afterwards. Mills (1992) followed the unusually swift accumulation of several 80-100 m thick talus cones during an 8-yr period after the 1980 eruption of Mount St. Helens, where rockwalls are also andesitic / dacitic. Most cones experienced a peak growth rate during the first 3 years, and although mass-wasting declined subsequently, rates are expected to remain high for some decades. Mills (1992: 745) even suggests that “...the most intense interval of mass wasting occurred within hours or days of the formation of the crater walls, when the cliffs were most out of equilibrium”. The description by Clark et al. (1972: 227) of rockfall activity also implies that cliff instability was highest within 2 or 3 years after the earthquake, with only “intermittent rockfalls” occurring by 1970.

The studies above indicate that multiple sizable rockfalls might have occurred in the weakened Crags cliffs following dome collapse, and that they would have swiftly added debris to the talus for some years, until the fractured dacite walls attained at least some precarious stability. In this view, the bulk of the debris on the Chaos talus arrived quickly after the 1675 volcanic explosion, although subsequent events (the steam eruptions of 1854-57, seismic activity) may also have dislodged much debris from the deeply fractured cliffs (Fig. 3). Photo repeat analysis does not disprove this hypothesis, as it indicates the Chaos talus has not changed significantly during the past century. Loomis (1926: 114) took a photograph, which included part of the talus, sometime between 1900 and 1910. (This photograph is not shown due...
to its poor, grainy quality). Williams (1928: fig. 7) replicated the view in 1927, but no major differences could be ascertained between the views. Comparison between 1927 and the present (Fig. 17) indicates a similar slope topography and little or no alteration in the outline of the rockwalls along their junction with the talus, but perhaps a slight upslope expansion of the talus areas covered by boulders. Tree cover has increased noticeably along the footslope during the past 70 years, and the density of shrubs (rock spirea) on blocks also appears to be somewhat higher (see Fig. 5).

In summary, the above findings would support the following conclusions:

(1) The lack of major distinctive morphological characteristics on the Chaos Crags talus does not support the hypothesis that debris were instantaneously deposited by VDA events. If such was the case, no unusual features created by the volcanic explosion have survived. Instead, the talus attributes examined suggest slope evolution by post-eruptive sedimentation.

(2) Due to the unstable nature of the brecciated rockwalls following dome collapse, the Chaos talus probably accumulated swiftly afterwards. Most debris presumably collected during a short period of a few years. However, without detailed cross-sectional observations of talus deposits (e.g., Hétu, 1995; Van Steijn et al., 1995) it is impossible to ascertain whether the nature of the geomorphic processes transporting rubble right after the collapse event was substantially different from that of processes observed today here or on nearby talus slopes.

(3) Some additional, but probably minor, volcanic or seismic events - such as during the period 1854-57 - may well have caused short bursts of debris accretion on the talus.

(4) Slope modification in the recent past and at present occurs by 'normal' mass-wasting processes, although grain flows are particularly active. This appears to be due to an ample supply of fine debris near the talus apex. However, photographs indicate only modest sediment additions and no obvious changes in overall talus morphology during the 20th century.

(5) It seems therefore entirely possible that much of the fine debris resting on the upper talus is part of the 'original' material deposited shortly after dome collapse. In this case, transport processes - though active - have lagged behind the vast initial delivery of debris to the talus.

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