



# Sackungen at the Aspen Highlands Ski Area, Pitkin County, Colorado



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## ABSTRACT

Numerous linear geomorphic features of suspected gravitational spreading origin, collectively termed sackungen, occur at elevations of 3,475–3,775 m at the head of the Aspen Highlands Ski Area near Aspen, Colorado. Features include double-crested ridges, upslope-facing scarps, linear troughs, and downslope-facing scarps. Most features are aligned with the prominent joint set (strike N25°–45°E, dip 80°–90° NW) that parallels the flanking, 1,150-m deep U-shaped glacial valleys of Castle and Maroon creeks. A backhoe trench 6 m long and 2 m deep was excavated across an upslope-facing scarp and adjacent trough to reveal the style and age of surface deformation. Sandstone bedrock of the Maroon Formation was extensively fractured under the scarp face, with abundant dilational voids. Hillslope colluvium was truncated at the main sackung fault plane, and was overlain by up to 1.2 m of fine-grained sag pond sediments. Seven buried soils were present in the trough fill, composed of A, and E or Bw horizons; A horizons at 35 cm, 84 cm, and 98 cm below the surface yield uncorrected <sup>14</sup>C ages of 3060±150, 6290±70, and 7910±80 <sup>14</sup>C yrs B.P., respectively. Extrapolation of deposition rates to the base of the fill indicates that the trough formed ca. 11–11.5 ka, several thousand years after glacial ice had melted from the flanking glacial valleys. Trench stratigraphy suggests that slow vertical offset across the trough has continued since 11 ka, at rates of 0.14–0.75 mm/yr, perhaps accompanied by horizontal spreading at 0.43 mm/yr in the past 3 ka. This rate of spreading is slower than the 1–5 mm/yr measured by Varnes and others (1990) across sackungen in the Sawatch Range to the east, but still constitutes a constraint on foundation design for buildings and lift towers.

## INTRODUCTION

Anomalous ridge-top troughs, closed depressions, and uphill-facing scarps were mapped during an environmental assessment of the Aspen Highlands Ski Area

(AHSA), Pitkin County, Colorado. Similar landforms described in the geologic literature are inferred to result from gravitational spreading of bedrock ridges. Because these features occurred in high-elevation areas proposed for future expansion of the ski area, we undertook detailed studies of one typical feature to confirm this suspected origin, and to characterize the subsurface geometry and spreading rates of such landforms. Of particular interest for engineering design of proposed buildings and lift towers was the style and sense of displacement across the spreading feature, and the current rate of movement (if any). Of more academic interest is the time of formation of the features, which are often attributed an early postglacial age (14,000–15,000 years in the Rocky Mountains; Porter et al., 1983) when located in glaciated terrain (e.g., Beck, 1968; Tabor, 1971). Previous workers have termed such features "sackungen" from the German word for sagging (Zischinsky, 1969; Radbruch-Hall et al., 1976). We adopt this term for the features in the Aspen area based on their similarity with European type examples. As increasing recreation-based development occurs in the mountainous regions of the U.S., more sackungen probably will be encountered and analyzed for their hazard potential.

## LOCATION AND LOCAL GEOLOGY

The study site is located 1 km SW of the town of Aspen, Colorado (Figure 1). This mountainous region lies at the intersection of the Precambrian-cored Sawatch uplift of Laramide age (50–70 Ma) to the east, and the late Paleozoic Eagle Basin to the west (Bryant, 1979). The Aspen Highlands Ski Area (AHSA) occupies a 1,000-m high, NNE-trending ridge bounded on the east and west by the deeply-eroded glacial valleys of Castle and Maroon creeks. The ridge is composed of a homoclinal, NNE-dipping sequence of late Paleozoic and Mesozoic sedimentary rocks (Figure 2). The high elevation part of the ridge, in which all sackungen are found, is underlain by the Pennsylvanian–Permian Maroon Formation. According to Bryant (1979), the Maroon Formation consists of grayish red to pale-red sandstone, siltstone, conglomerate, mudstone, and limestone (in order

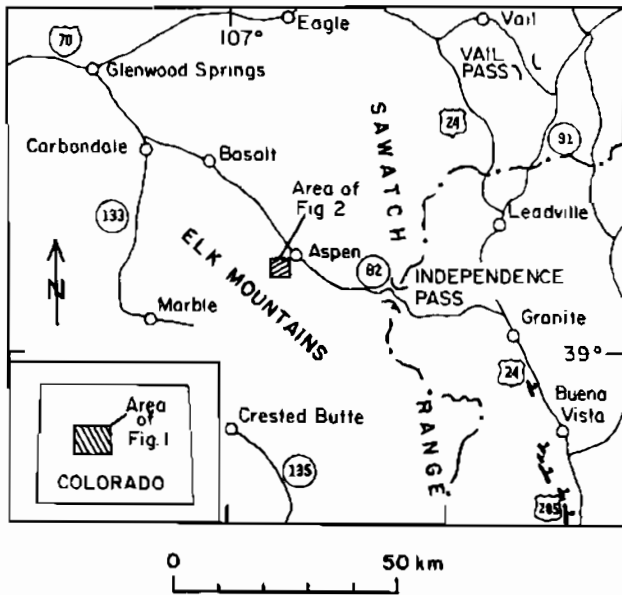


Figure 1. Regional location map of the study area. Late Quaternary normal fault scarps of the Sawatch fault (from Kirkham and Rogers, 1981) are show by heavy lines in lower right, ball on downthrown side.

of decreasing abundance), interbedded on scales of 30 cm to 10 m. At the AHSA, only the uppermost 1,000 m of the 3,200-m thick Maroon Formation is exposed. Dominant lithologies in this part of the stratigraphic section are fine- to medium-grained micaceous sandstone and red siltstone, with bed thicknesses of 5–100 cm. Bedding strikes between N30°–55°W and dips from 25°–45° NE, so that beds dip parallel to the ridge crest. Two prominent joint sets are approximately perpendicular to bedding, the major one striking N25°–45°E and dipping 80°–90° NW, the minor one striking N70°W and dipping 55°SW. Joints are typically spaced 10–30 cm apart and this spacing determines the dominant dimensions of the abundant residual, frost-shattered rock rubble that mantles hillslopes above and near timberline.

PREVIOUS WORK ON SACKUNGEN

Zischinsky (1966, 1969) first proposed the term “sackung” for the surface manifestations of deep-seated rock creep in foliated bedrock of the Alps. (In this paper we use the term “sackung” to refer to the process of seep-seated sagging, and “sackungen” to refer to the surface forms created by that process). An inventory of published sackung scarp dimensions (McCleary et al., 1978, Table 2) yields these typical ranges: scarp length, 15–300 m; scarp height, 1–9 m; slope height, 400–1,200 m; slope gradient, 25°–50°. Varnes and others (1989) distinguish three types of sackung: a) spreading of rigid rocks overlying soft rocks (Radbruch-Hall, 1978; Radbruch-Hall et al.,

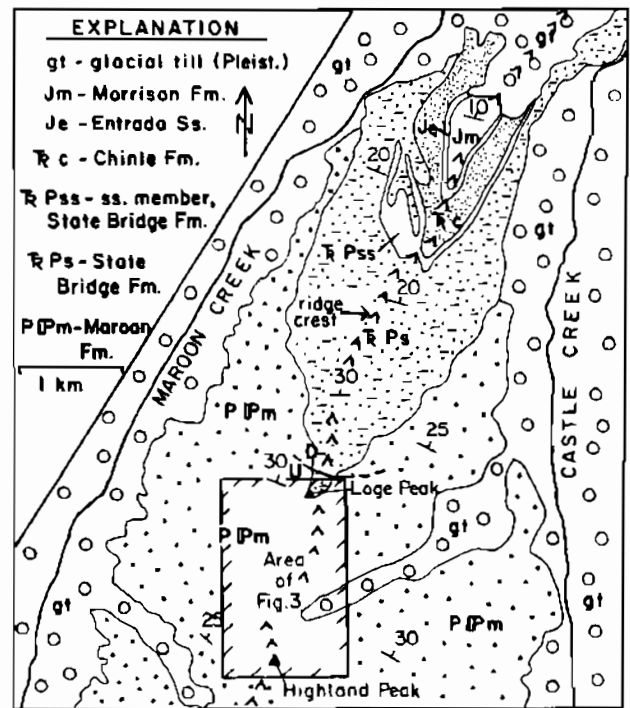


Figure 2. Simplified geologic map of the Aspen Highlands Ski Area and vicinity. The open circles show late Pleistocene till in the U-shaped valleys of Maroon and Castle creeks. Late Paleozoic and Mesozoic sedimentary rocks dip uniformly 10°–30° NNE (mapping adapted from Bryant, 1971, 1972).

1976), b) sagging and bending of foliated phyllites, schists, and gneisses (“true Sackung” of Zischinsky, 1969), and c) differential displacements in hard but fractured crystalline igneous rocks. The phenomena described herein most closely resemble type c, but are developed in massive competent sandstone rather than in intrusive rocks. Sackungen have been observed in almost all rock types, including phyllite and schist (Jahn, 1964; Zischinsky, 1969; Nemcok, 1972; McCleary et al., 1978; Ertec Northwest, Inc., 1981; Morton and Sadler, 1989; and Clague and Evans, 1994), slate (Goodman and Bray, 1976), high-grade gneisses and intrusive rocks (Radbruch-Hall et al., 1976, 1977; West, 1978; and Varnes et al., 1989, 1990), volcanic rocks (Tabor, 1971; Bovis, 1982; and Beget, 1985), and massive sedimentary rocks (Beck, 1968; Radbruch-Hall, 1978).

Two opposing hypotheses have been proposed for the subsurface geometry of sackung in massive competent rocks. The first hypothesis, held by Zischinsky (1969), Mahr (1977), and other European and American workers, proposes that “a well-defined slide plane near the headscarp passes downward into a broader zone of rock creep. Consequently the lower portion of this type of failure simply bulges out into the valley” (Morton and Sadler, 1989, p. 302). The slide plane may dip either into or out of the slope. Such slow, deep-seated failure results in “half-a-landslide” morphology (Morton and Sadler,

1989), with well-developed tensional features near the head, but often with no recognizable evidence of medial landslide features or compressional morphology at the toe. Although Radbruch-Hall (1978) claims that rock creep can extend to depths of several hundred meters, there are few locations where the depth or shape of the failure plane can be measured with certainty, thus this hypothesis cannot be tested directly.

The second hypothesis is that sackungen are shallow surface manifestations of toppling and flexural slip along discontinuities that dip steeply into a mountain mass, but which do not penetrate to any great depth (Jahn, 1964, Figure 9; Beck, 1968; and Bovis, 1982). Bovis termed this process "flexural toppling" and cited model studies (Barton, 1971) and studies in quarries (Goodman and Bray, 1976) as support for a this non-penetrative mode of extensional deformation. In flexural toppling, outward rotation of blocks and dilation of sackung cracks lead to attenuation of movement with time, which Bovis (1982) compared to strain-hardening in granular materials.

The stress field that produces sackung may have five possible origins: a) ice wedging (the original explanation for European sackung; Zischinsky, 1969), b) gravity forces that produce deformation slowly to the point of instability in a rock mass, c) stored forces resulting from prior loading conditions (e.g., glaciation) that produce sporadic deformation as strain is recovered, d) seismic shaking that induces lateral spreading and differential settlement of rock masses, and e) displacement connected to deep-seated seismogenic faults (Erteç Northwest, 1981).

The ice wedging theory has largely been abandoned since it has been observed that sackung spreading extends to great depths and occurs in temperate climates. Recent modeling of stresses in long symmetric ridges (Savage et al., 1985; Savage and Swolfs, 1986; Pan and Amadei, 1994; and Pan et al., 1994) provides theoretical support for origin b, especially where weak foliated rocks are present. Proponents of origin c point out that sackungen are common in areas of high relief, especially where valley walls were "oversteepened" by Pleistocene valley glaciers. Augustinus (1995) suggests that most glacially "oversteepened" slopes are actually in strength equilibrium (Selby, 1993), and while subject to slow strain, will not fail catastrophically. Many authors (Beck, 1968; Radbruch-Hall, 1978; and Bovis, 1982) have suggested a causal relationship between the retreat of a valley glacier that once buttressed a steep slope, and the subsequent sagging and bulging of the slope. Tabor (1971) noted that sackungen are wide-spread only where ridges rise more than 1,000 m above glaciated valleys. Supporters of origin d, working in active seismic areas, have noted sackungen on lower-relief slopes, and have ascribed the spreading to either general earthquake shaking and settling (Beck, 1968; Solonenko, 1977; Clague, 1979, 1980; and Nolan and Weber, 1992), concentration of rock

shattering on ridge crests by topographic amplification (Morton et al., 1989), or to surface fault rupture (e.g., Cotton, 1950). The sackungen landforms cited as evidence for the various theories described above all look remarkably similar, perhaps because they reflect the geometry of deep-seated failure regardless of how it was initiated.

### SACKUNGEN AT ASPEN HIGHLANDS

Sackungen are found dominantly along ridge crests and at the top of steep cirque headwalls (Figure 3). With the exception of the curvilinear scarps around the rim of the Highland Bowl (Figure 3), most sackungen are linear, 200–500 m long, and trend between N25°–45°E, parallel to the major joint set (strike N25°–45°E, dip 80°–90° NW) in the Maroon Formation (Figure 4). The geomorphic

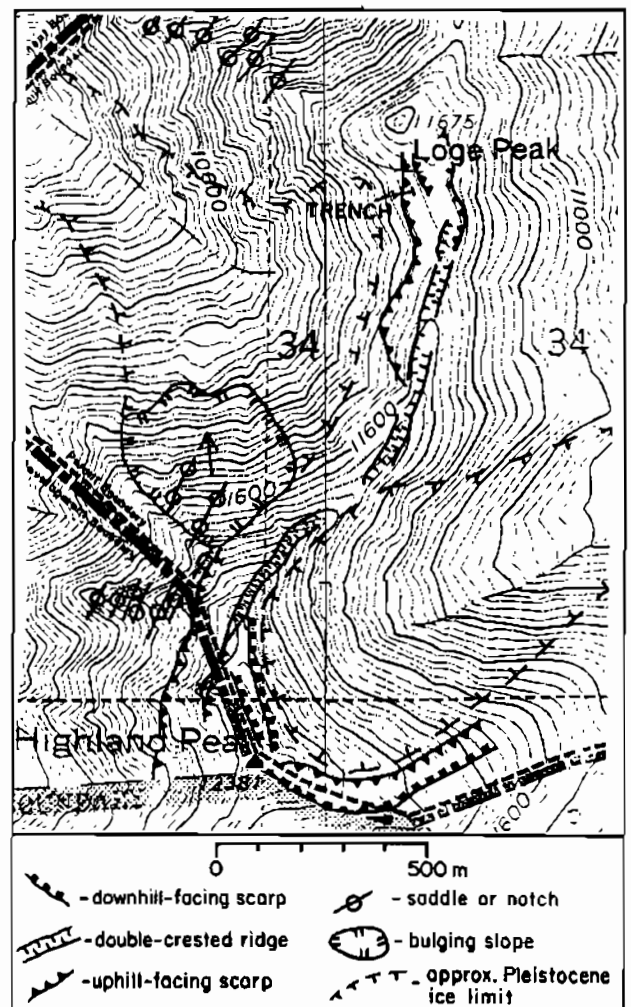


Figure 3. Geomorphic map of sackungen in the AHSA. Contour interval is 12.2 m (40 ft). Cirques are outlined by the approximate Pleistocene ice limits (trimlines). The Highland Bowl is at lower right, Maroon Bowl is at upper left. Arrow indicates possible movement direction of bulging slope at the head of the Maroon Bowl.

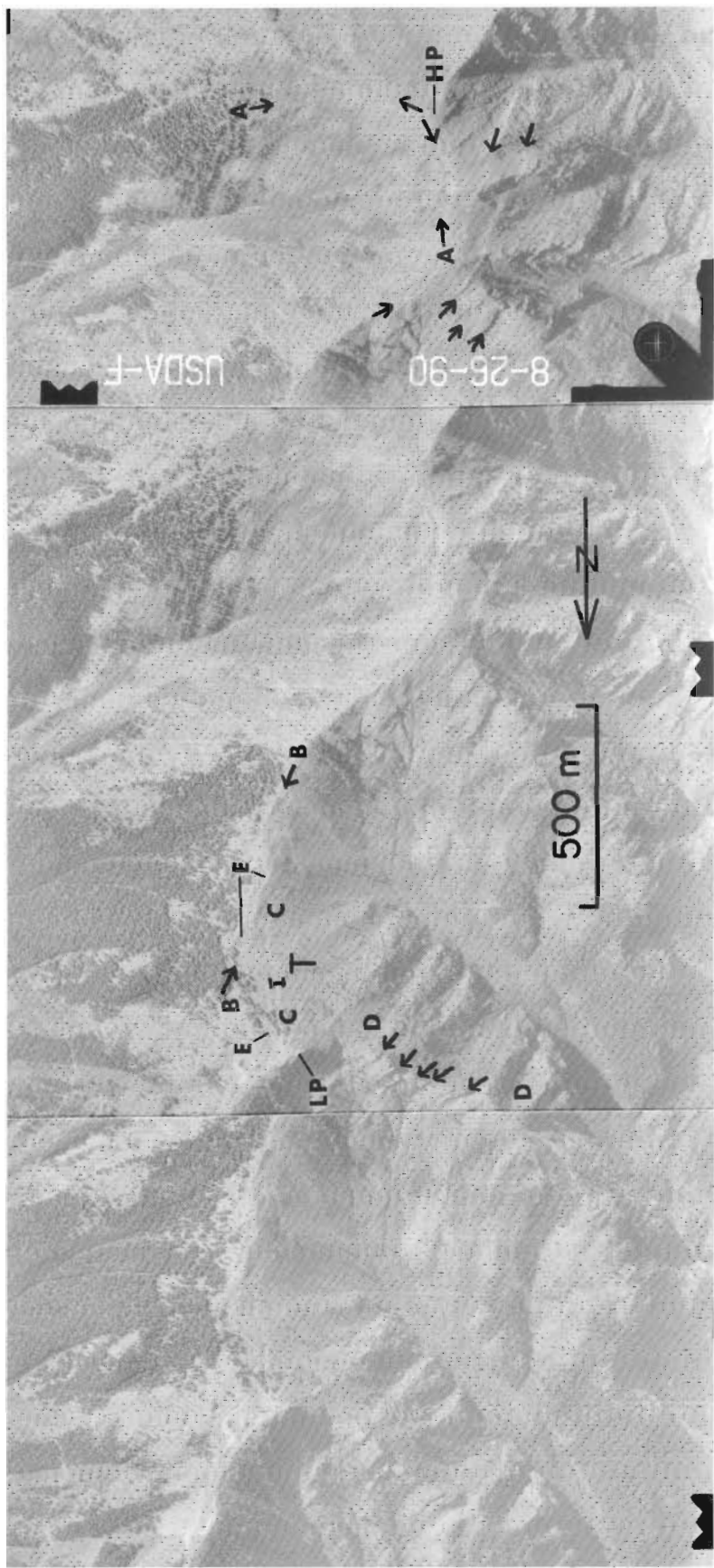


Figure 4. Stereo aerial photographs of sackungen at the AHSA. Arrows show scarps, troughs, and notches. The areas between arrows labelled "A" through "D" show locations of ground photographs in Figure 5A through D, respectively. "E"'s indicate closed depressions. The short heavy line marked by "T" indicates the location of the backhoe trench. LP = Loge Peak, HP = Highland Peak.

features can be divided into four categories: downhill-facing scarps, double-crested ridges, uphill-facing scarps, and erosional notches on ridge axes.

#### Downhill-Facing Scarps Along Cirque Headwalls (Figure 5A)

Downhill-facing scarps are best expressed around the rim of the Highland Bowl (Figures 3 and 4) and form a semicircle around the cirque headwall. At the head of the cirque the scarps are 3–8 m high and are separated by surfaces that slope toward the scarp and create topographic depressions at the foot of the scarps. At the ends of the semicircular pattern this back-tilted block geometry gradually changes to one of asymmetrical

gullies as the gradient of the affected ridge crests steepen. Part of the vertical relief in these gullies may be due to erosion, but the transverse asymmetry persists and indicates that the gullies are still structurally controlled. At the extreme eastern end of the Highland Bowl sackung complex the gullies gradually change shape downslope into more symmetrical channels typical of fluviially-eroded landforms.

These headwall scarps are similar in morphology to landslide headscarps formed by downslope translation or rotation of bedrock blocks. In the AHSA, however, there is no evidence of a distinct landslide toe on the cirque headwall below the scarps. Nowhere has the cirque headwall bulged outward sufficiently to create rockfalls or topples due to oversteepening. The slip on failure



Figure 5. Ground photographs of sackung features: A) Downhill-facing scarps immediately NNW of Highland Peak. Photo was taken from the summit of Highland Peak looking NW; vertical distance between “a”s is 8 m. LP = Loge Peak, valley of the Roaring Fork River in distance. B) Double-crested ridge between Highland Peak and Loge Peak (just off photo at upper left corner), looking NNE. Vertical distance from the bottom of the axial trough to the top of flanking ridges is 2–3 m. Footpath in the center is 0.5 m wide. Photograph was taken from the location marked “B”. C) Uphill-facing scarps are in the meadow south of Loge Peak, view to SE. The trench site is shown by a horizontal bar with “T”. D) Saddles and notches (small arrows) are on the axis of a steep ridge descending to Maroon Creek (valley in background), looking SW. Note the wedge failure (large arrow at far right) defined by sackung notch (farthest right vertical arrow).

planes beneath these scarps thus cannot be detected in the geomorphology of areas downslope, either because slip was too small (< 10 m), and/or because the deformation was distributed in a broad zone of rock creep.

Double-Crested Ridges (Figure 5B)

Double-crested ridges (the "Doppelgrate" of Zischinsky, 1969) are a classic sackung landform. The axial depression typical of Doppelgrate is difficult to explain by an erosional process, because streams are unlikely to flow down the crest of a ridge and the closed depressions could not have been excavated by running water. The long ridge between Loge Peak and Highland Peak (Figure 3) displays a double crest with intervening swales or closed depressions over much of its 1-km length. Ridges such as these are inferred to have undergone lateral spreading (Zischinsky, 1969; Varnes et al., 1989), with the central depressions representing either graben (Figure 6A) or headscarps of downslope movements (Figure 6B) similar to that shown in Figure 5A.

Uphill-Facing Scarps (Figure 5C)

Uphill-facing scarps and sidehill benches are the most common sackung landform, both in the AHSA and elsewhere in Colorado (Varnes et al., 1989). Scarps are typically 0.5–2.0 m high, 150–600 m long, trend approximately parallel to slope contours, and bound linear

troughs that lie upslope of each uphill-facing scarp. Where scarps are nearly parallel to contours, the accompanying linear troughs form topographically closed depressions up to 4 m deep. Where scarps trend diagonally across slopes, the accompanying troughs are modified by the action of running water, an effect which increases with slope angle. Troughs that traverse hillslopes mantled with residual, frost-shattered rock rubble, are typically filled with a matrix-free assortment of angular sandstone blocks ranging from 10–30 cm in diameter. A tape measure can be lowered between these blocks to depths up to 1 m, either indicating that the rubble is that thick or that joints in the underlying bedrock are dilated.

A common microgeomorphic phenomenon is the occurrence of circular depressions on the scarp face and at its base. These depressions are 0.1–1.0 m in diameter, 30–40 cm deep, and are filled with coarse, angular rock rubble with no matrix. Open void spaces are common, and some can be traced down 0.5–1.0 m into open vertical fissures in bedrock.

Saddles, Notches, and Wedge Failures on Ridge Axes (Figure 5D)

On the western flank of Highland Peak several steep ridges descend more than 1,000 m to the valley floor on either side of a cirque informally named the Maroon Bowl. These ridges are split by numerous saddles and notches along the steep ridge crest. The notches are only visible on the treeless parts of the ridge above the Pleistocene glacial trimline of the Maroon Creek valley, but may also extend below the treeline. While a sackung origin for these notches cannot be proven, their parallelism with other unambiguous sackungen, and their sudden appearance above the glacial trimline are consistent with a spreading origin related to deglacial unloading. Several bedrock wedge failures occur on the steep ridges, apparently failing down the line of intersection between bedding planes dipping at 25°–45° and dilated sackung (?) joints dipping 80°–90° (Figure 5D, lower right).

THE TRENCH SITE

Geomorphology

The site for detailed study is a gently-sloping meadow located approximately 200 m south of Loge Peak (Figure 3). We chose this uphill-facing scarp and its associated trough for excavation because the closed depression had a lush grass cover that suggested the presence of thick, fine-grained trough sediments, possibly containing interbedded buried organic soil horizons. The trench was aligned perpendicular to the strike of the sackung scarp and trough, with the downslope end of the trench placed in a shallow circular depression on the

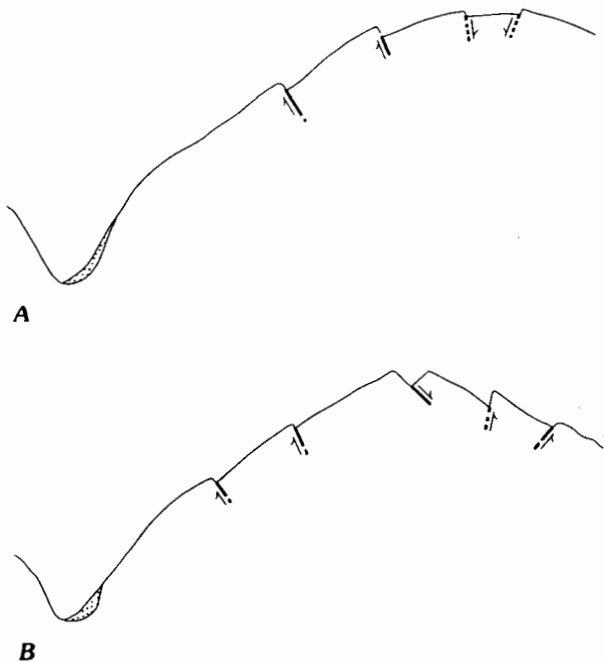


Figure 6. Sketch of typical profiles across spreading ridges in massive crystalline rocks. A) Summit graben and uphill-facing scarps; B) Double-crested ridge and uphill-facing scarps (from Varnes et al., 1989, Figure 3).

## Trench Stratigraphy

scarp face (described previously). The floor of the trough at the trench site exposed only fine sandy sediments and a lush grass cover suggestive of seasonal ponding.

The scarp forms the upslope face of an asymmetric bedrock ridge, the outer (downslope) face of which is the unmodified hillslope. Scarp faces in this area expose bedrock in their upper half, with finer scarp-derived colluvium covering the lower scarp face and grading into fine-grained trough fill sediments. On the unmodified hillslopes between the scarps, those sections immediately downslope of the sackung ridges expose bedrock at the surface, perhaps the result of erosional stripping of colluvium. Farther downslope, the colluvial mantle thickens until it reaches a thickness of ca. 1 m immediately upslope of the sackung trough.

The scarp is only 1.2 m high at the trench site, but if we assume that the hillslope on either side of the scarp was originally continuous, the slope has experienced a net vertical surface offset of 4 m along the structure that underlies the scarp (Figure 7). The hillslope below the sackung is ca. 5° steeper than that above the sackung (Figure 7), a geometry associated by Jahn (1964) with outward toppling. If the 15 m portion of hillslope downslope of the scarp toppled outward by 5°, that rotational motion would induce an apparent component of vertical surface offset equal to  $15 \text{ m}(\sin 5^\circ)$ , or 1.3 m. This value is smaller than the 4 m of surface offset observed. The disparity implies that, unless toppling involved slopes beyond the surveyed cross-section, there must be some component of dip-slip displacement on the structure beneath the scarp.

The trench exposes eight lithologic units under the scarp face and trough (Figure 8). The first unit is sandstone bedrock of the Maroon Formation (B in Figure 8A) that underlies the scarp face and contains pockets of coarse, angular rock rubble. Bedding in the fine-grained micaceous sandstone is well-defined, with beds 15–30 cm thick, and attitudes of N80°W, 40°NE to N25°W, 55°NE. The trough is underlain by seven unconsolidated deposits. The lower deposit (unit 7, Figure 8A) is a reddish gravelly sand that contains an increasing number of angular sandstone clasts near the bottom of the trench. Based on the presence of these clasts and the difficulty of excavation below them, we infer that intact bedrock lies immediately under the trench floor. The gravelly sand appears to be locally derived from weathering of Maroon Formation sandstone and contains occasional well-sorted lenses of subangular granule gravel suggestive of sheetflow deposition or dry ravel. We thus infer that unit 7 represents hillslope colluvium derived from weathering of exposed sandstone bedrock. The colluvium abruptly terminates in a vertical contact with shattered bedrock in the center of the trench.

The upper unconsolidated deposits (units 1–6, Figure 8A) comprise a series of fine-grained trough fill sediments and interbedded soil horizons. These sediments do not resemble the underlying colluvium in either color or texture, being buff to brown rather than red and composed mainly of silt with little sand and no clasts. Based on the fine grain size, anomalous color, and rich organic nature of interbedded soils, we infer that these sediments

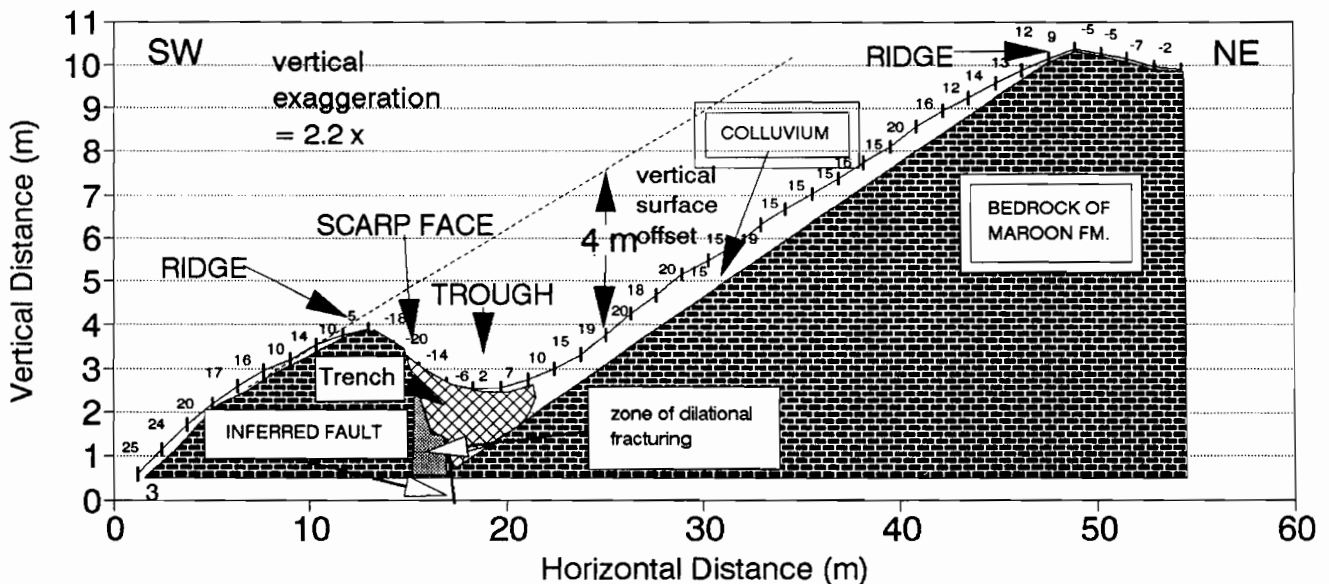


Figure 7. Generalized geologic cross-section across the uphill-facing scarp at the trench site. Small numbers above the ground surface show inclination of surface slope segments in degrees. The backhoe trench is shown by crosshatched area. The thickness of colluvium (unshaded) is inferred except at the crest of scarps and in the trench.

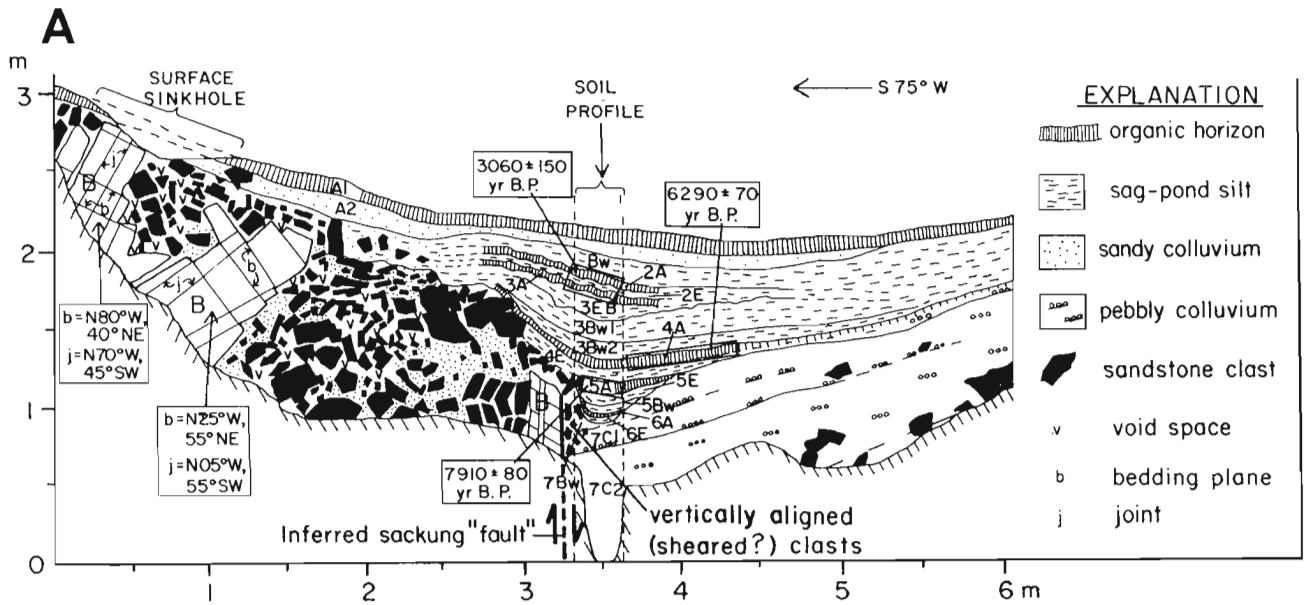


Figure 8. A) Log of the trench across the sacking scarp and trough. In intact bedrock masses (“B”) b = attitude of bedding, j = attitude of joints. Radiocarbon ages (in boxes) are in radiocarbon years before present; see Table 2 for calendar-corrected ages. Stratigraphic units 1–8 described in the text are indicated by parent material numbers in the soil profile; B) Photograph of trench wall. Intact rock at lower center is marked by a “B” on the trench log, and immediately abuts the sacking fault plane. Note open void spaces at left center and lower left. Soil horizon 4A is the prominent black band at right center, which is bent upward as it approaches the sacking fault plane.

accumulated in a closed depression that occasionally held ponded water. The source of such brown silt-rich sediments on a landscape composed of red sandstone is somewhat problematic, especially considering the site has an extremely small catchment area only 100 m below the ridge crest. Much of the silt fraction may be eolian material that was retransported downslope by sheetwash and deposited in the depression formed by the sacking scarp.

### Vegetation and Soil Development

The present trough surface is covered by *Carex* and *Juncus* spp. which prefer abundant moisture and indicate episodic standing water in the trough. Slopes around the trough are covered by *Thurber fescue* which has replaced *Engleman spruce* and *subalpine fir* following a fire 25–100 (?) years ago. The soil profile beneath the grassy trough is atypical of other profiles described on the

Maroon Formation elsewhere in the AHSA (Irvine, 1993), but is similar to other soils developed in closed depressions in till at the foot of the ridge (Figure 2).

Soil profile development holds clues to the geomorphic development of the sackung trough. The lowermost horizons (7Bw, 7C1, 7C2) are similar in color and texture to cambic and substratum horizons observed elsewhere on planar surfaces over the Maroon Formation. The 7Bw horizon was probably the ground surface of the pre-sackung landscape. Horizons above the 7Bw horizon all consist of silt loams (Table 1), composed of fine to very fine sand, silt (the dominant component) and clay. Based on the high silt content and lack of internal stratification, we infer that creep, rainsplash, and perhaps minor sheetwash were the dominant depositional mechanisms. The lack of stratification within each unit may also suggest that units 1–6 were deposited rapidly in single severe events. Severe remobilization of surface silt in this environment is best explained by forest or grass fires that removed stabilizing vegetation and exposed bare soil; erosion would then cease once vegetation was reestablished. Horizons 4E, 3Bw1, 3Bw2, and Bw contain fine detrital charcoal fragments that support the theory of rapid deposition following fires.

Units 2 through 5 contain A/E, A/EB, or A/Bw horizon sequences that indicate the presence of forest cover at the trough. We infer that the forest canopy in this area was generally intact during the initial formation of the sackung and deposition of units 5–6, based on the limited thickness of those units and lack of detrital charcoal. Units 3 and 4 (46 cm and 15 cm thick, respectively)

represent major depositional events, but consist only of silt loam with no indication of coarser clastics either shed from the sackung scarp, or transported by concentrated flow from upslope. Unit 2 represents a minor depositional event, followed by increased sedimentation and later soil formation (horizons A1, A2, Bw).

High-chroma mottling in horizons A2, 2E, 3A, 3EB, 5Bw, and 6E is caused by iron oxidation and indicates that water moves freely through the profile. The lack of evidence for reducing conditions is puzzling given the topographic and vegetation evidence for seasonal ponding of water in the trough. Evidently ponded water drains downward rapidly through the trough fill sediments, probably using the open fractures along the sackung fault plane (next section).

### Structure

Three distinct structural elements can be defined in the western (bedrock) part of the trench. The first element is three quasi-intact blocks of Maroon sandstone bedrock, indicated by "B"s in Figure 8. Within the western and eastern blocks bedding is consistent at N80°W, 30–40°NE, which matches the regional strike and dip elsewhere on the AHSA mountain ridge. The middle block has apparently toppled forward (eastward) 0.8–1.3 m and pulled away from the western block, judging from the 10°–15° steeper attitude of bedding. Joints and bedding planes within these blocks are predominantly tight, except for the western half of the eastern block where joints have been dilated to 1–2 cm wide,

Table 1. Description of superposed soils in the sackung trench.

Horizon	Depth (cm)	Color <sup>1</sup>	Texture <sup>2</sup>	SD:SI:CL <sup>3</sup>	Structure	pH
A1	0–7.5	7.5YR 4/2	SiL	20:65:15	granular	5.2
A2	7.5–15	5YR 5/3	SiL	15:49:16	subang. blocky	5.2
Bw	15–29	5YR 5/4	SiL	25:59:16	subang. blocky	5.6
2A	29–33	5YR 5/2	SiL	10:72:18	subang. blocky	5.4
2E	33–38	7.5YR 6/2	SiL	10:70:20	subang. blocky	5.4
3A	38–42	7.5YR 5/2	SiL	10:70:20	angular blocky	5.2
3EB	42–56	7.5YR 7/4	SiL	10:72:18	angular blocky	5.6
3Bw1	56–72	5YR 6/4	SiL	10:74:16	subang. blocky	5.4
3Bw2	72–84	2.5YR 6/6	SiL	10:78:12	angular blocky	5.4
4A	84–89	7.5YR 4/2	SiL	10:74:16	subang. blocky	5.4
4E	89–99	5YR 7/4	SiL	10:72:18	subang. blocky	5.4
5A	99–104	7.5YR 4/2	SiL	10:72:18	subang. blocky	5.2
5E	104–109	5YR 7/2	SiL	10:72:18	subang. blocky	5.0
5Bw	109–114	7.5YR 6/4	SiL	10:70:20	subang. blocky	5.6
6A	114–118	7.5YR 4/1	SiL	10:72:18	subang. blocky	5.6
6E	118–122	7.5YR 7/3	SiL	15:67:18	angular blocky	5.4
7Bw	122–135	2.5YR 6/4	SL	70:22:8	subang. blocky	5.2
7C1	135–140	2.5YR 6/4	S	96:2:2	single grain	5.6
7C2	140–213	2.5YR 6/6	SL	60:28:12	massive	5.4

<sup>1</sup> Munsell color of dry peds.

<sup>2</sup> SiL = silt loam; SL = sandy loam; S = sand.

<sup>3</sup> SD:SI:CL = weight percentages of sand:silt:clay

The second element is large zones of loose angular sandstone clasts (rock rubble) separated by open void spaces. The western of these zones directly underlies the circular surface sinkhole, which suggests that subsurface toppling (inferred earlier from bedding attitudes) slowly opened a V-shaped void between the bedrock blocks. That void then partially filled with angular rubble, leaving the surface sinkhole. The fresh morphology of the sinkhole implies that toppling may still be active, otherwise locally-derived eolian and slopewash materials would have filled in the depression. The larger rubble zone in the west-central part of the trench contains both open voids between blocks and some sandy matrix (Figure 8). The end of a tape measure could be lowered as much as 1 m below the trench floor through some of these open voids, suggesting that joints in the underlying sandstone were standing open.

The third structural element is the vertical bedrock contact under the center of the trench. This contact underlies the thickest part of the trough fill and abruptly truncates slope colluvium unit 7. Because neither the grain size or dip in the colluvium changes as it approaches this contact, it seems clear that the colluvium was deposited on the hillslope before the formation of the sackung scarp. No colluvium exists on the upper part of the outer (downslope) side of the sackung ridge (Figure 7), so we presume it was removed by erosion following differential uplift across the sackung scarp. This vertical contact is the main sackung "fault" along which vertical movement and/or toppling has occurred. Above the sackung fault, sediments and soils of the trough fill are abruptly tilted to dips far in excess of reasonable primary depositional dips for fine sediments. Older soils in the trough fill are progressively more tilted as they approach the sackung fault, indicating progressive movement throughout deposition. The overall geometry of the fault zone is reminiscent of dip-slip displacement in plastic sediments, such as described in trenches by Clark and others (1972).

A minimum estimate of the cumulative vertical displacement (throw) of trough fill could be made if the initial dip and westward extent of unit 6A were known. The most conservative assumption is that such a richly organic A horizon was originally horizontal on the trough floor, and that it extended at least as far west as its preserved extent. An alternative assumption is that the western part of this soil (as well as that of soils 5A and 4A) was eroded off the upthrown block after uplift. Under this assumption, throw can be estimated by presuming that soil 6A originally extended as far west as soils 2, 3, and 4 (0.9 m farther SW than present), and was later tilted from a 0° dip to its present maximum dip of 75±5°. By trigonometry, the throw associated with 75±5° of tilting over a horizontal distance of 0.9 m equals 2.5–5.1 m, which is in the same range as the 4 m of vertical surface offset between bedrock at the trench floor and the projected bedrock surface shown in Figure 7. This computed

value implies that much of the earlier trough fill sediments (units 4–6) have been eroded off the upthrown block. Smaller values of throw can be calculated in the same manner for soils 4A and 2A+3A (Figure 9A), based on their maximum dips of 45±5° and 18±5°, respectively. Based on the assumptions of original horizontality and lateral extent, it appears that roughly 75 percent of throw occurred before 7 ka, and that throw has continued at a slower rate since 7 ka.

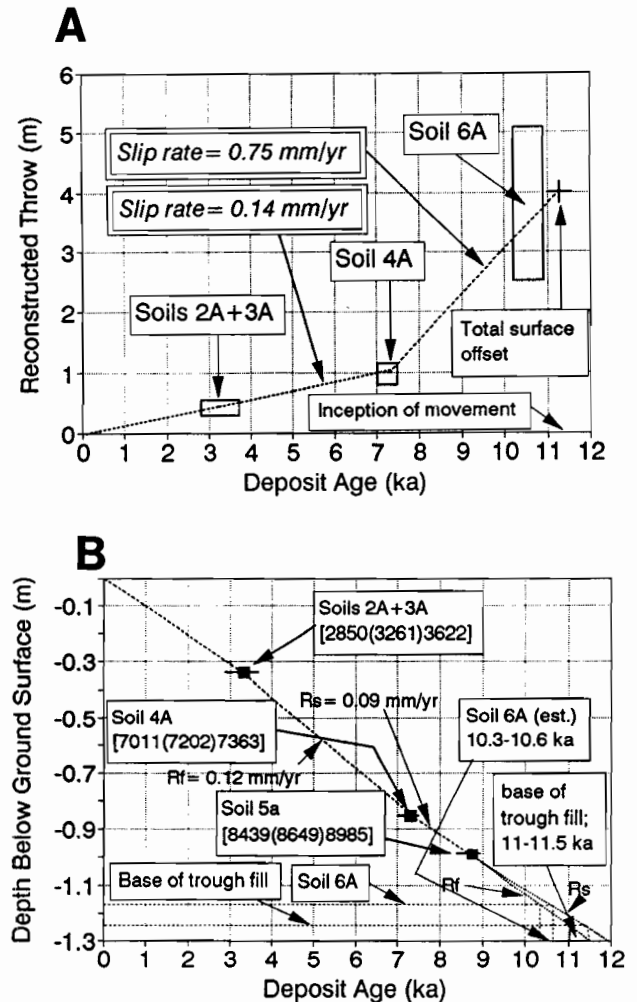


Figure 9. A) Reconstructed throw for three soils and total surface offset, as a function of deposit age. Horizontal dimension of boxes is defined by 1-sigma limits of calendar-corrected ages (Table 2). The age for soil 6A is derived from extrapolation in Figure 9B. Vertical dimensions of boxes represent the range of throws resulting from uncertainty in maximum dip angle for each soil used in the trigonometric calculations (see text). The dotted line shows apparent vertical slip rates on the sackung fault. B) Deposit age (Table 2) as a function of depth below the ground surface in the trough fill. The dotted line shows apparent deposition rates: Rf = fast deposition rate, Rs = slow deposition rate. Depending on which deposition rate is extrapolated to the bottom of the trough fill, the inception of sackung movement ranges from 11–11.5 ka.

Table 2. Summary of radiocarbon ages.

Lab. No. <sup>1</sup>	Unit	Material	Laboratory Age ( <sup>14</sup> C yr B.P.) <sup>2</sup>	Calendar Age (cal. yr B.P.) <sup>3</sup>
β-67363	2A+3A <sup>4</sup>	charcoal	3060±150	2850(3261)3622
β-67364	4A	charcoal	6290±70	7011(7202)7363
β-67365	5A	charcoal	7910±80	8439(8649)8985

<sup>1</sup> Beta Analytic, Inc.

<sup>2</sup> Conventional decay-counting technique; uncorrected for <sup>13</sup>C content.

<sup>3</sup> According to Stuiver and Reimer (1993); mean age in center, flanking ages represent 1σ limits.

<sup>4</sup> A composite sample from both horizons.

### Geochronology

Conventional radiocarbon ages were obtained from three of the buried A horizons in the trough fill (Table 2). Each dated horizon contained macroscopic charcoal which was hand-picked and cleaned. The ages of units 4A and 5A are based on thin (<3 cm thick) samples, but due to low carbon content soils 2A and 3A had to be sampled together. Laboratory radiocarbon ages (such as shown in Figure 8A) were corrected for secular variations in <sup>14</sup>C production and converted into calendar years before present (cal. yr B.P.), using the calibration program of Stuiver and Reimer (1993). All rates of deformation and sedimentation (e.g., Figure 9) are computed in calendar years for consistency, and deposit ages are cited in ka (1 ka = 1,000 cal. yr B.P.).

The age of soils as a function of depth below the ground surface (Figure 9) indicates fairly uniform silt deposition rates between periods of soil formation. Rates range from a slow rate (Rs on Figure 9B) of 0.09 mm/yr between 7,202–8,649 cal yr B.P., to an intermediate rate of 0.11 mm/yr between 3,261 cal yr B.P. and the present, and to a rapid rate (Rs in Figure 9B) of 0.12 mm/yr between 3,261–7,202 cal yr B.P. The fast and slow rates, when projected downward, yield estimated ages of 10.3–10.6 ka for soil 6A, the oldest soil developed in the trough fill, and an age of 11–11.5 ka for the base of the trough fill (unit 6Bw/7 contact). This latter age is the closest approximation to the time of formation of the sackung scarp and trough.

### DISCUSSION

#### Geometry and Origin of Sackungen at the AHSA

Sackungen at the AHSA are found only where the maximum mass has been removed from the ridge flanks by headward erosion of the Highland and Maroon cirques (Figure 3). Almost all sackungen are linear and parallel to the dominant N25°–45°E joint set in the Maroon sandstone. Artificial cuts for ski facilities have shown that joints of this orientation at the ridge crest stand open 3–5 cm at depths of up to 15 m below the

original ground surface (Figure 10). The implication of these observations is that sackungen are caused by near-surface lateral spreading perpendicular to the ridge crest. It is not possible to state whether the failure mode is deep-seated sliding or shallow flexural topping, because no toe bulges are observed. Tracing the fracture zones downward via geophysical techniques was considered impractical due to the homogenous nature of the Maroon Formation and the minor displacement across the sackung fault.

Of the four origins for sackungen mentioned previously, ice wedging can be ruled out because no cryogenic features (involutions, ice-wedge casts) are observed in the silty trough fill, even though silt is very susceptible



Figure 10. Photograph of open (dilated) joint on the floor of a 15-m deep cut into the State Bridge Formation (Permian–Triassic), approximately 400 m north of Loge Peak. Numbers on tape measure are inches. End of tape could be lowered 1.5 m into this joint.

to ice wedge growth (e.g., Black, 1976). Seismogenic faulting can be ruled out based on the lack of mapped displacement of the stratigraphic sequence (Figure 2). A seismic shaking origin is unlikely because the latest paleoearthquakes dated on the nearest seismic source (the Sawatch fault, Figure 1) likely occurred between 12–25 ka (Ostenaar et al., 1981), whereas continued sackung deformation has occurred from ca. 11 ka to present. The two remaining origins (gravity forces and stored forces) would both give rise to the slow, continuous deformation inferred from trench stratigraphy. However, the pattern of high initial (pre-7 ka) rates of deformation followed by slower rates is consistent with strain recovery against late Pleistocene glacial loading.

### Style and Rate of Surface Deformation

It appears that sackung deformation in the near-surface environment has several different styles, based on scarp morphology and our single trench. Most of the relief of the trenched sackung scarp was created by near-vertical slip along a discrete steeply-dipping fault plane that is located beneath the toe of the surface scarp (Figure 8A). The only other trench log of a sackung scarp of which the authors are aware (McCleary et al., 1978, Figure 21) shows a subvertical fault plane in a similar geomorphic position. Natural exposures of sackung trough fill in the North Cascades, Washington, also show subvertical fault planes (Beget, 1985). If fine-grained sediments accumulate in the trough, the style of subsequent surface deformation appears to be bending of these ductile sediments over the projection of the fault plane. Such bending implies slow, continuous slip on the underlying fault plane. We see no evidence of coarse debris (colluvial wedges) shed from a free face on the sackung scarp, which would be expected if displacements were episodic.

A second type of movement is horizontal extension indicated by the forward-toppling subsurface block of bedrock in the trench. It is possible that horizontal extension has been the main mode of deformation for the past ca. 3 ka, because the sinkhole above the topple disrupts units 1, 2, and 3, but these units show negligible bending above the main sackung fault. Dividing the 1.3 m horizontal separation by 3 ka yields a maximum horizontal spreading rate of 0.43 mm/yr for this sackung scarp.

Two possible scenarios can explain the geometry of sediments and soils in the trench. The first scenario would involve continuous slip on the sackung fault at rates of 0.14–0.75 mm/yr (Figure 9A) over the past 11 ka. During that time, periods of slopewash into the trough alternated with periods of surface stability in which the six soils formed. In this scenario, the thickness of the trough sediments and the degree of development of the soils has no relation to the chronology of sackung slip, but rather reflects the severity of slopewash

on slopes above the trough. Periods of alternating deposition and stability may be related to Holocene climate changes or to local perturbations such as forest fires. This scenario is our preferred interpretation at the trench site, although it would not necessarily apply to all sackungen sites.

A second scenario would assume a more direct causal link between slip on the sackung fault and sedimentation in the trough. In this scenario, slip on the sackung fault would occur episodically rather than continuously, and the thickness of stratigraphic units in the trough would reflect the additional topographic closure created in each successive movement. In this model, soils would indicate periods of sackung inactivity, and thick silt units would represent pulses of sedimentation following abrupt sackung slip episodes. Such a connection between faulting, sedimentation, and soil formation has been extensively documented in trenches across active dip-slip faults (e.g., Schwartz and Coppersmith, 1984; Machette et al., 1992; and McCalpin et al., 1994). However, we feel that there are major differences between the stratigraphic relations in a typical active fault exposure and those exhibited in the sackung trench. At active fault scarps, the sediment that buries the soils is colluvium shed from the fresh scarp face produced by faulting; if a graben is present, coarse colluvial wedges interfinger with finer graben sediments (Swan et al., 1980; McCalpin et al., 1994). At the sackung trench, in contrast, the sediment that buries the soils is not coarse angular blocks that would be shed from a fresh exposure of shattered sandstone bedrock, but is fine sand and silt that probably came from sheetwash upslope. We observed no lenses of rubble (debris-facies colluvium of Nelson [1992]) to overlie the buried soils near the scarp toe, as would be expected if fresh scarps had been created during sackung slip. Subsidiary faulting of the hanging wall is also commonly associated with discrete fault displacements (McCalpin, 1987), but no subsidiary faults are visible in the sackung trench. We thus conclude that the trenched scarp does not move episodically, and that continuous creep (scenario 1) is the likely mode of deformation.

Data in Figure 9 show the sackung was originally produced about 11–11.5 ka. Numerous radiocarbon ages indicate that deglaciation of mountain valleys in Colorado following the last glacial maximum (20–22 ka) had been fully completed by 14–15 ka (e.g., Porter et al., 1983). If the buttressing effect of valley ice was removed no later than 14–15 ka, why did the sackung not begin to form until 11–11.5 ka? One answer is that the strain recovery took 2.5–4.0 ka to propagate from the glacial trimline at an elevation of 3,110 m to the trench site over 1,000 m farther up the ridge flank at an elevation 3,490 m. Bovis (1982, his Figure 11) constructed a series of diagrams showing how retrogressive movement may have occurred in British Columbia, but the diagrams do not have spatial or temporal scales. McCleary and others

(1978) and Ertec Northwest, Inc. (1981) described a similar upslope-younging of sackungen in the North Cascade Range, whereas Beget (1985) documents scarps that cross-cut each other on the same ridge crest.

### Mitigation of Sackung Hazard

The ground displacements caused by sackung are slow, but pose some threat to structures anchored into bedrock across sackungen. For example, the concrete pads of ski lift towers could split or tilt under vertical or horizontal strain. The most serious hazard is due to vertical displacement, which can evidently average 0.14–0.75 mm/yr over long time spans. An associated hazard is horizontal extension (at rates up to 0.43 mm/yr) across sackungen due to fracture dilation and flexural toppling, as observed in the trench. Rates even higher than this were measured by Varnes and others (1990) across multiple sackungen 40 km east of Aspen in the Sawatch Range. Horizontal movements of up to 70 mm (average 20–30 mm) occurred there between 1975–1989, yielding cumulative spreading rates of 1.4–5.0 mm/yr for an entire mountainside.

If structures must be placed across sackungen, mitigation should begin with excavation of the openwork rubble zones beneath the scarps and the compressible fine-grained trough sediments. Grouting of open fractures beneath the scarps might decrease infiltration rates and diminish the potential for downward piping, but if sackung dilation continues new fractures will be opened. An alternative mitigation against piping is placing a woven geotextile at the base of the excavation, and backfilling with a structural fill, such as done for subsidence fissures (e.g., Werle and Stilley, 1991). Once the subgrade is prepared, foundation options include: a) placing structures on a gravel pad that can absorb extensional strain, b) reinforcing foundation elements by post-tensioning, and c) providing for re-leveling of foundations in case of tilt.

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