Topographic and Structural Conditions in Areas of Gravitational Spreading of Ridges in the Western United States

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Topographic and Structural Conditions in Areas of Gravitational Spreading of Ridges in the Western United States

By D. J. VARNES, D. H. RADBRUCH-HALL, *and* W. Z. SAVAGE

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A study relating gravitational spreading of ridges to local topography and geologic structure

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TOPOGRAPHIC AND STRUCTURAL CONDITIONS IN AREAS OF GRAVITATIONAL SPREADING OF RIDGES IN THE WESTERN UNITED STATES

By D. J. VARNES, D. H. RADBRUCH-HALL, and W. Z. SAVAGE

ABSTRACT

Gravitational spreading of steep-sided ridges produces characteristic geomorphic forms including grabens and depressions along ridge crests, trenches, and uphill-facing, as well as downhill-facing scarps, on the mountain flanks, and outward bulging of the lower slopes. These sackung-type features occur in a variety of geologic settings in the Western United States. Those discussed here occur principally in high, linear ridges separated by glaciated valleys. The ridges are underlain by hard, but closely jointed, Precambrian igneous rocks. Topography is the primary determinant of the location and direction of the trenches and scarps, but the topographic grain of the terrane is, itself, determined in part by rock structures, such as joints and faults. In the Sawatch Range in Colorado, some valleys in the study area follow the direction of primary joint systems and, in turn, determine the direction of trenches and scarps parallel to slope contours. The principal joint sets are, themselves, parallel to microcracks in the rocks. The relation of sackung features to structural elements is close in the Sawatch and Williams Fork Mountains in Colorado, not obvious at the one site examined in the Sangre de Cristo Mountains of New Mexico, close in the Stillwater Complex in Montana, and apparently close in a zone around the Straight Creek fault in the northern Cascade Mountains in Washington. Elastic-plastic stress analysis indicates that uphill-facing scarps may develop in the upper extending parts of a slope preferentially over downhill-facing scarps.

INTRODUCTION

Large-scale, deep-seated distortion of steep-sided ridges has come under increasing study both abroad and in the United States during the past 20 years. One impetus for study of these features comes from the resemblance of their surface morphologic features, primarily scarps, to those of recent faults, and the need to identify and quantify fault movements and recurrence intervals for a variety of construction activities. Although the scarps observed are technically fault surfaces, they result from the local adjustments within steep-sided ridges rather than far-field tectonic stresses. Making the distinction from tectonic faults is not always simple, for scarps due to local movement often follow pre-existing discontinuities in rock masses, including tectonic faults, joints, cleavage, schistosity, or foliation.

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The forms of sagging developed in the steep-sided slopes depend very much on the lithology of the masses involved, the degree of development of existing discontinuities, and the relation of the strike and dip of anisotropic elements to the direction and angle of dip of the slope. Three general lithologic settings may be distinguished: (1) massive, strong (although jointed) rocks lying on weak rocks; (2) ridges composed generally of metamorphosed rocks with pronounced foliation, schistosity, or cleavage; and (3) ridges composed of hard, but fractured, crystalline igneous rocks. Slope deformations in all these settings have been referred to by many authors, including ourselves, variously as "sackungen," from the German word for sagging, or by the term "deep-seated creep." As the name implies, these features can be shown to result from large-scale gravitational spreading (Radbruch-Hall and others, 1976; Savage and Varnes, 1987). The mode of origin is illustrated in this report in the section "Elastic-Plastic Stress Analysis of Gravitating Ridges."

Sackungen of the first type, involving the spreading of rigid rocks overlying soft rocks, have been described previously (Radbruch-Hall, 1978). Gravitational spreading for this case was modeled by finite-element analysis (Radbruch-Hall and others, 1976). These kinds of movement are not discussed here.

The second type shows features as described in detail by Zischinsky (1969) from the Austrian Tirol, and was referred to by him as "true Sackung." This involves much more extensive sagging and bending of foliated schists, phyllites, and gneisses than is found in more homogeneous and competent rocks.

Our attention in the present report is directed mainly at sackungen of the third type, and we are concerned with mostly ridges above glacially oversteepened valleys in Precambrian granite and migmatite in central Colorado and to features in some other localities in the Western United States. The mechanics of gravitational spreading of such ridges of more or less homogeneous crystalline rocks are not well understood. Hence, as part of the study of the origin of sackung features, we have considered their relation to topography and to local and regional structure.

In 1977 and 1978, sites were visited at Bald Eagle Mountain, Surprise Ridge, and Mount Nast in the granite and gneiss of the Sawatch Range in Colorado, and sites in layered basic igneous rocks of the Stillwater Complex in Montana were also visited (figs. 1, 2). Brief reconnaissances were made of parts of the Williams Fork Mountains of Colorado (fig. 2) and of the Cascade Mountains east of Seattle, Wash. In the Sawatch Range, the orientations of jointing and foliation were measured and oriented samples were taken, from which thin sections were made.

In 1981, sackungen were examined in more detail in the Williams Fork Mountains, particularly near Ute Peak and Old Baldy, where jointing and foliation were measured. In 1982, additional observations were made at Mount Nast and Surprise Ridge, a large sackung was examined on Mount Massive, and others were investigated in the Sangre de Cristo Mountains of New Mexico between Taos and the southern border of Colorado (fig. 1, locality 5). Jointing and foliation were measured at each of these localities.

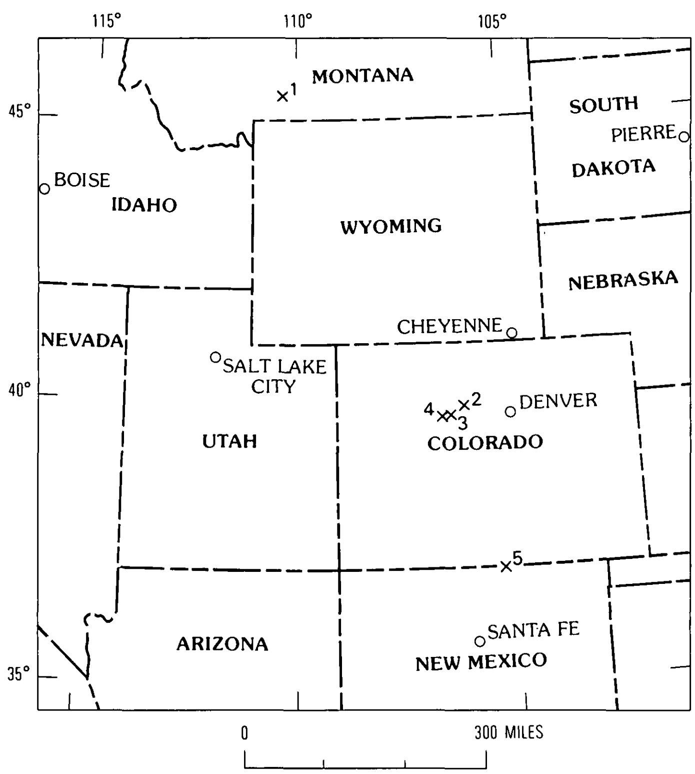


FIGURE 1.—Index map showing location of sites in the Rocky Mountains of the Western United States discussed in the text. (1) Stillwater Complex, Montana; (2) Williams Fork Mountains, Colorado; (3) Bald Eagle Mountain and Mount Massive, Colorado; (4) Mount Nast-Surprise Ridge, Colorado; (5) Site in the Sangre de Cristo Mountains, New Mexico.

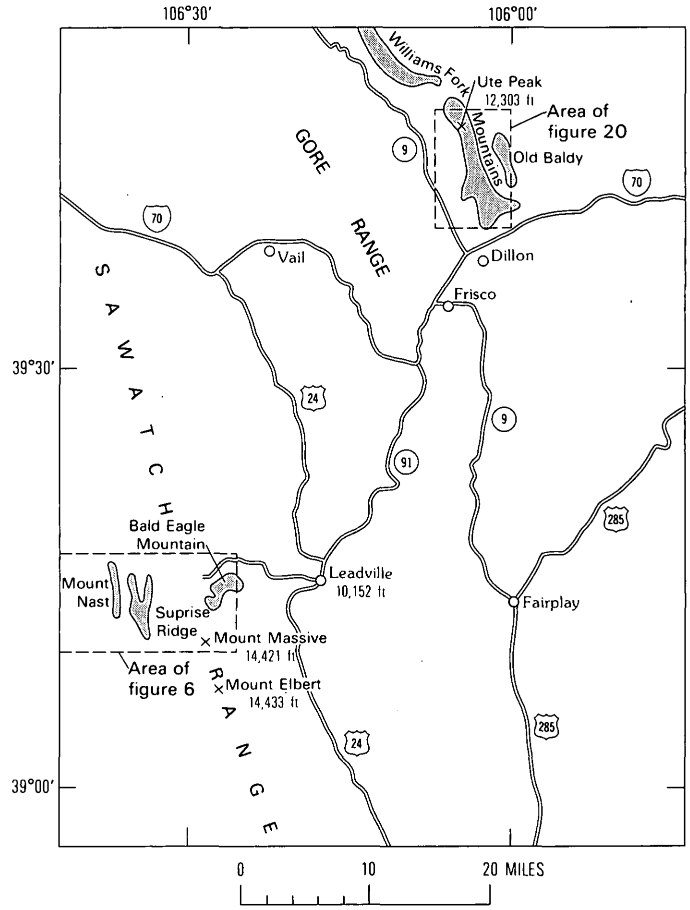


FIGURE 2.—Index map showing by dashed rectangles the location of study areas in the Williams Fork Mountains and Sawatch Range, Colorado.

The sackungen we have studied have the following characteristics, not all of which may be developed at any one locality:

1. Uphill-facing scarps on the slope, one to a few meters high, trending approximately parallel with topographic contours and commonly somewhat convex downslope in plan. The trenches so produced are asymmetric in profile: The steep, upward-facing scarp is on the downhill side of the trench; the gentler, uphill side appears often to be an unmodified hillslope.
2. A graben or grabens along the ridge crest, commonly with closed contours and ephemeral ponds.
3. Double-crested ridges.
4. Bulging of the lower parts of the slopes.
5. Occurrence on the upper flanks of glaciated valleys, with the movement apparently being post-glacial.
6. Local relief more than 1,000 ft.
7. Occurrence more common on massive and often somewhat rounded ridges, rather than on narrow ridges between cirques. Profiles across spreading ridges of type 3 are shown in figure 3.

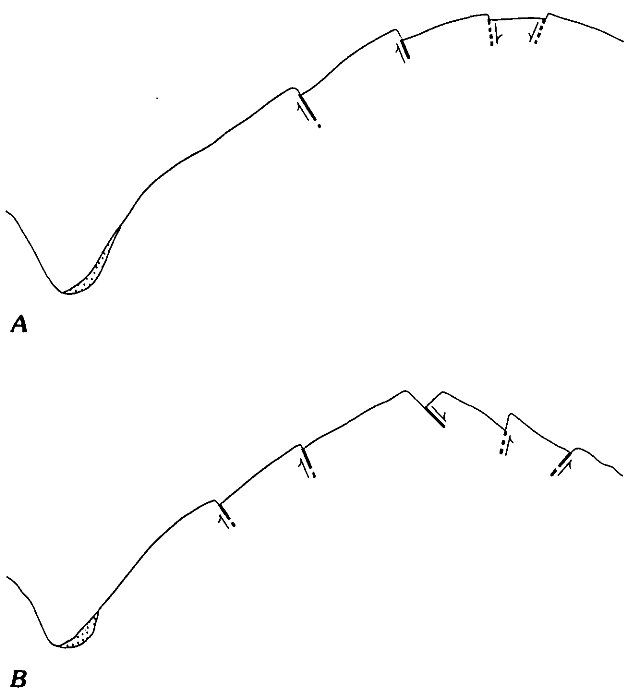


FIGURE 3.—Sketch of common profiles across spreading ridges in hard, jointed crystalline rocks (sackung, type 3). *A*, With ridge-top graben; *B*, With double-crested ridge. The lower parts of the originally glaciated valleys have been modified by bulging and the accumulated debris of talus and rock falls. Arrows indicate sense of relative displacement along fractures.

LOCALITIES IN THE SAWATCH RANGE, COLORADO

BALD EAGLE MOUNTAIN AND MOUNT MASSIVE

A ridge-top graben and hillside trenches mark a major sackung feature on a broad ridge that extends southwestward from Bald Eagle Mountain, 9 mi west of Leadville, Colo. A mass of rock on the northwest side of the ridge has moved northwestward toward the valley of Busk Creek (figs. 4, 5). The geologic map of the Bald Eagle–Mount Massive area (eastern portion of fig. 6), indicates that the rock exposed is granitic (Yg), which, here, consists of gneiss cut by stringers and masses of granite and pegmatite rock. Figure 6 shows the sackung trenches on Bald Eagle Mountain, as well as joint and foliation attitudes. The graben and trenches trend approximately N. 50° E. Joints and foliation are locally well exposed in fresh rock in a cirque on the southeast side of the ridge, northeast of Rainbow Lake. The major joint set in the cirque trends N. 47–67° E. and dips 73–85° SE. (fig. 7). Foliation, as well as a secondary set of joints parallel to the foliation, trends approximately N. 45° W. and dips 30–40° NE. A prominent joint set at the north end of Bald Eagle Mountain strikes N. 17–20° E. and dips 42–64° NW. (fig. 6). Joint spacing is from less than 1 in. up to 6 ft, with most being spaced from 6 in. to 2 ft apart.

Triangulation-trilateration nets established at Bald Eagle Mountain in 1975 and 1977 were remeasured in 1982 and extended in 1984. No movements in excess of expected surveying errors have been detected.

A pronounced trench is visible on a cirque wall on the northwest slope of Mount Massive, about 3½ mi southwest of the Bald Eagle sackung locality (fig. 6). Here, coarse-grained, somewhat foliated granitic rock is cut by well-developed joints from a few inches to more than 6 ft apart. A large and deep, northeast-facing cirque lies directly below and north of the highest point on Mount Massive. It is separated from a much shallower basin to the northwest by a narrow, northeast-trending ridge. A block of rock approximately 3,000 ft long and 200 ft wide has separated from the ridge and has moved down and out toward the large, steep-walled cirque to the southeast, forming a long, northeast-trending trench and uphill-facing scarp on the gentle, northwest-facing slope of the shallower basin northwest of the ridge (fig. 8). For much of its length, the face of the uphill-facing scarp consists of plane surfaces that are the walls of joints that trend N. 20–35° E. and dip 62–77° SE. This trend is somewhat more northerly than that of the Bald Eagle sackung trenches and that of the major joints in the cirque between Bald Eagle Mountain and Mount Massive. Other joints in the face of the uphill-facing scarp on Mount Massive trend N. 5–50° W. and dip 22–74° NE. In places, joints follow the foliation, which is variable.

JOINT ATTITUDES

Figure 9 shows the poles, plotted on a Wulff stereographic net, of planes of joints and foliation in the Bald Eagle–Mount Massive area. There is a good deal of scatter of the joint directions and dip, particularly of the less well-developed joint sets. Foliation is generally not well developed here. A concentration of poles of the most prominent joint set is visible in the northwest and southeast quadrants of the diagram indicating a tendency towards a northeast strike of the main joints. A concentration in north-northeast strike is more easily seen in figure 10, in which the arcs of intersection of planes on the lower hemisphere are plotted for the most prominent joint at each place of observation. Observations of principal joints at three places at the foot of a very steep slope below the lowermost trench in areas where bulging, dilation, and possible rotation of blocks is to be expected are plotted in figure 10 as dashed lines.

FIGURE 4.—Aerial oblique view looking northeastward down the valley of Busk Creek. On the broad southwest ridge of Bald Eagle Mountain to the right, a ridge top shallow graben and trenches high on the northwest slope are outlined by snow. Also marked by snow is a bench about halfway up the slope, trending parallel to the contours.

We have not observed sackung-type trenches and scarps in essentially unjointed rock. Nor have we observed a shear surface cropping out at the base of a slope that has trenches and scarps. Thus, one of the requirements for a ridge of granitic rock to undergo creep movement appears to be that the rock mass is closely divided by joints so that relative displacements of a flow-like character can occur without the necessity of a through-going basal slip surface. To obtain some quantitative measure of the degree to which rock in the Bald Eagle Mountain area is divided, we measured the joint spacing in bedrock exposures and the size of loose blocks on the surface.

JOINT SPACING

The spacing of joints of in-place bedrock was measured at several localities in the Bald Eagle area as shown in table 1. The spacing of joints having the orientation recorded in column 2 of table 1 was measured on intersecting joints having the orientation shown in column 3.

JOINT BLOCK SIZES

Measurement of the longest, shortest, and intermediate dimensions were made of 100 randomly selected blocks lying loose along the low scarp on the northwest side of the shallow graben on the crest of the southwest ridge of Bald Eagle Mountain. The longest long dimension was 44 in., the median long dimension was about 11.5 in. The longest short dimension was 26 in. The median volume, assuming a rectangular prismatic shape, was 437 cubic in.

Measurements of 25 blocks at triangulation station 3, just below the lowest trench, yielded roughly comparable results. The longest long dimension was 44 in., the longest short dimension was 16 in., and the median volume was approximately 1,200 cubic in., considerably larger than the median volume at the ridge top graben. The reason for this difference is unknown.

MOUNT NAST AND SURPRISE RIDGE

Sackungen are well developed in the Sawatch Range west of Bald Eagle Mountain, on Mount Nast, west of

(Continued on p. 9)

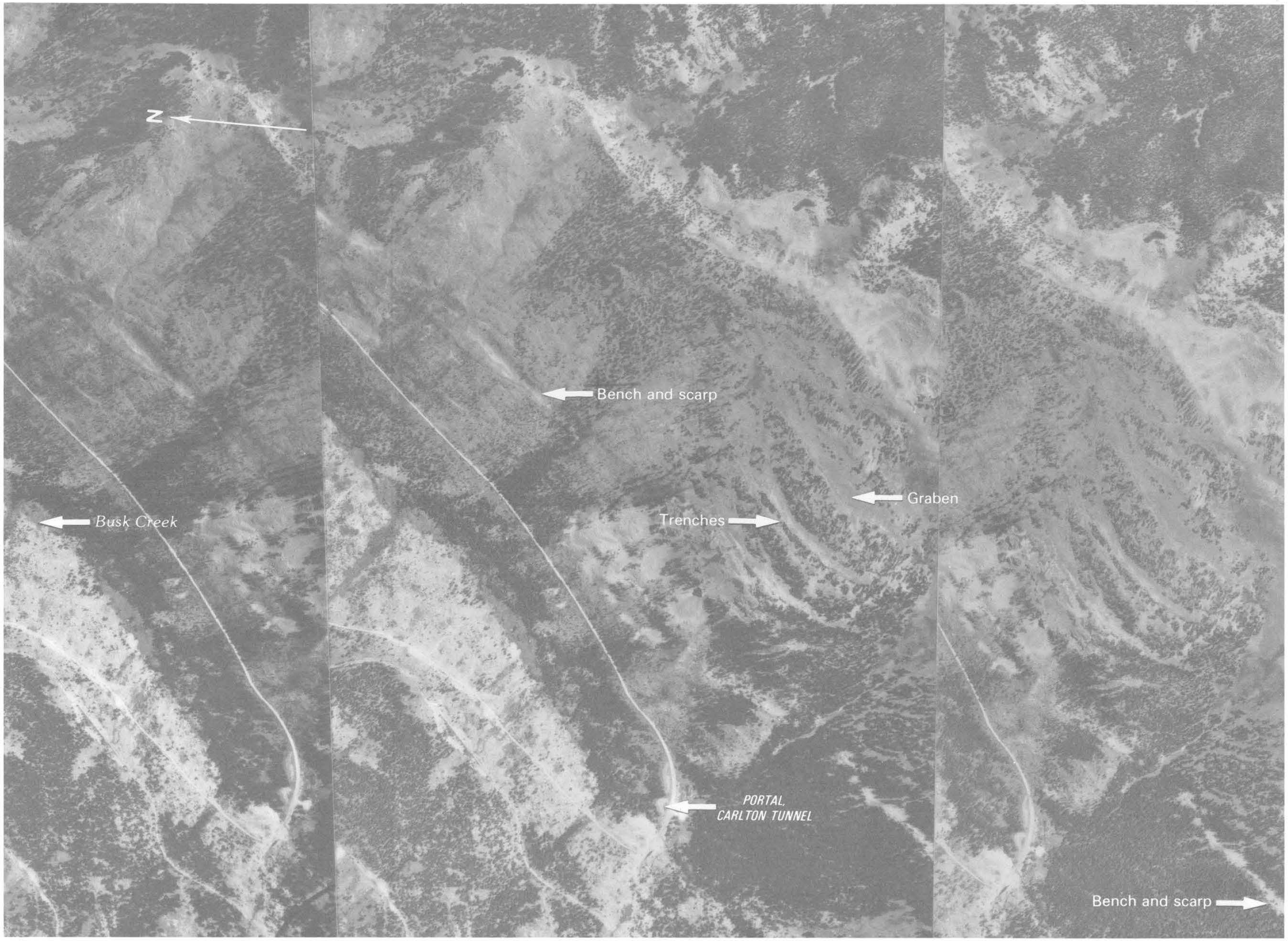


FIGURE 5.—Stereotriplet from vertical aerial photographs of the Busk Creek–Bald Eagle Mountain area, showing principal area of trenches on the slope southeast of Busk Creek and the graben near the ridge crest. A prominent bench with scarp on its uphill side extends along the slope parallel to the contours. The scarp is obscured by rock-fall deposits in the vicinity of the bulge of the slope below the trenches. The Carlton Tunnel diverts water from the west side of the Continental Divide southeastward into the Busk Creek drainage.

Base from U.S. Geological Survey, 1:50,000
Pitkin County and Lake County,
Colorado, 1975

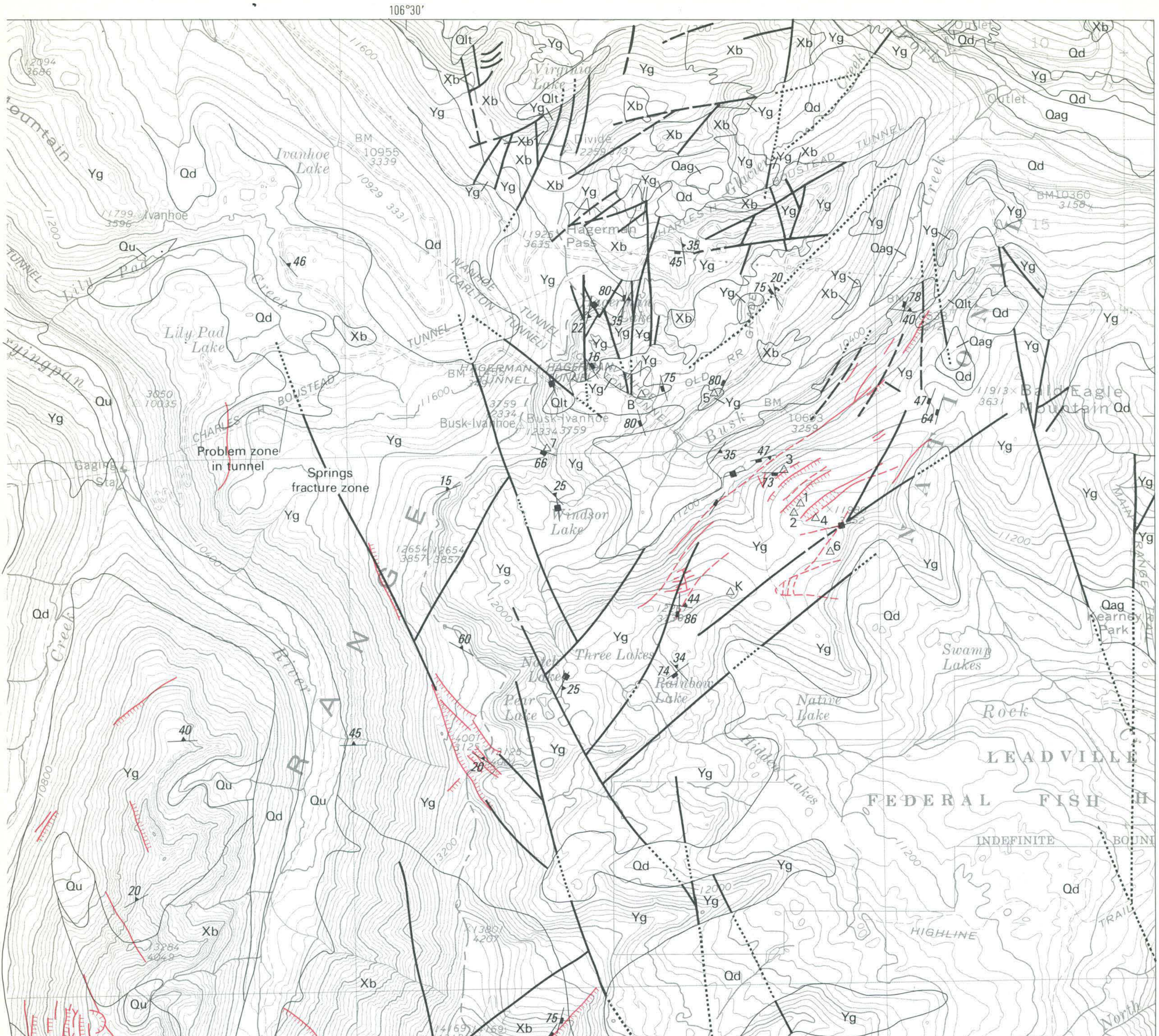
106°37'30"

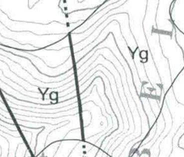
SCALE 1:50 000

1 ½ 0 1 2 MILES

1 .5 0 1 2 KILOMETERS

CONTOUR INTERVAL 80 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929





LOCATION MAP

EXPLANATION

QUATERNARY	Qag	Alluvium and stream gravels, bog deposits
	Qlt	Landslide and talus deposits
	Ql	Landslide deposits
	Qd	Glacial drift
MIDDLE PROTEROZOIC	Yg	Granitic rocks of ≈1,400 m.y. age group
EARLY PROTEROZOIC	Xb	Biotite gneiss and schist, migmatite

Qu — Non-glacial surficial deposits undivided

Contact

Fault—Dashed where approximately located or where concealed

40 Strike and dip of foliation

60 Strike and dip of joint set

Vertical joint

△3 Triangulation-trilateration station

Linear feature of probable gravitational origin—Dashed where location uncertain

Scarp of gravitational origin—Teeth on downthrown side

FIGURE 6 (above and 2 previous pages).—Geologic map of the Mount Nast–Surprise Ridge (western part) and Bald Eagle Mountain–Mount Massive (eastern part) study areas. Geology in western part by Ludington and Yeoman (1980) and in the eastern part by Tweto (1974) and Tweto and Reed (1973a). Linear features and scarps and some joint observations added by Varnes, Radbruch-Hall, and Savage.

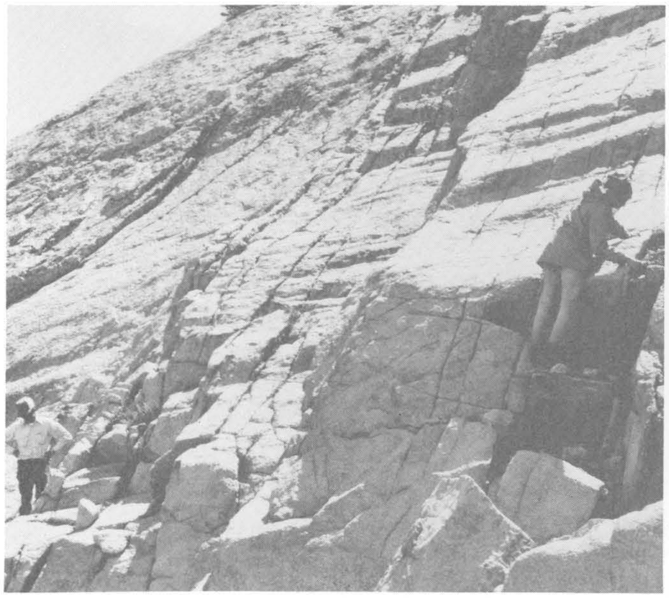


FIGURE 7.—Prominent joints striking N. 47–67° E. and dipping 73–85° SE. exposed in the headwall of a cirque on the southeast side of the Bald Eagle ridge, northeast of Rainbow Lake.

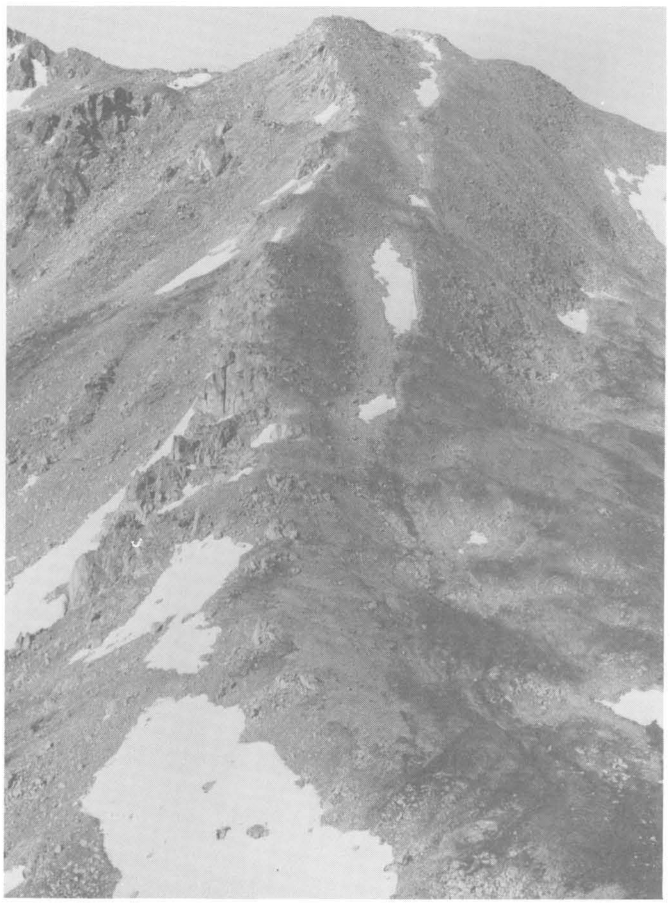


FIGURE 8.—Aerial oblique view looking southwest at the trench on a northeast-trending ridge northwest of the high point of Mount Massive. The trench apparently was formed when a block of rock approximately 3,000 ft long and 200 ft wide moved down, to the left, toward a large, steep-walled cirque.

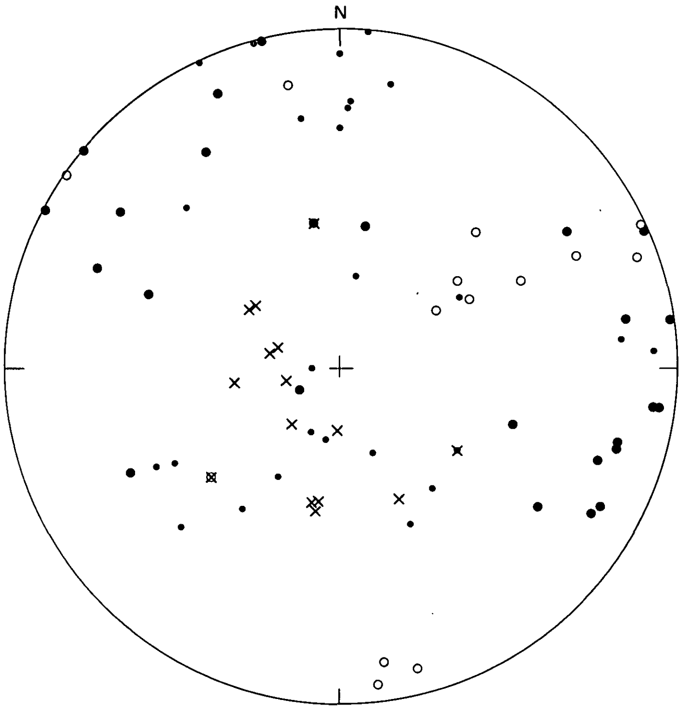


FIGURE 9.—Poles of joints and foliation observed in the Bald Eagle Mountain–Mount Massive area, plotted on a Wulff net.

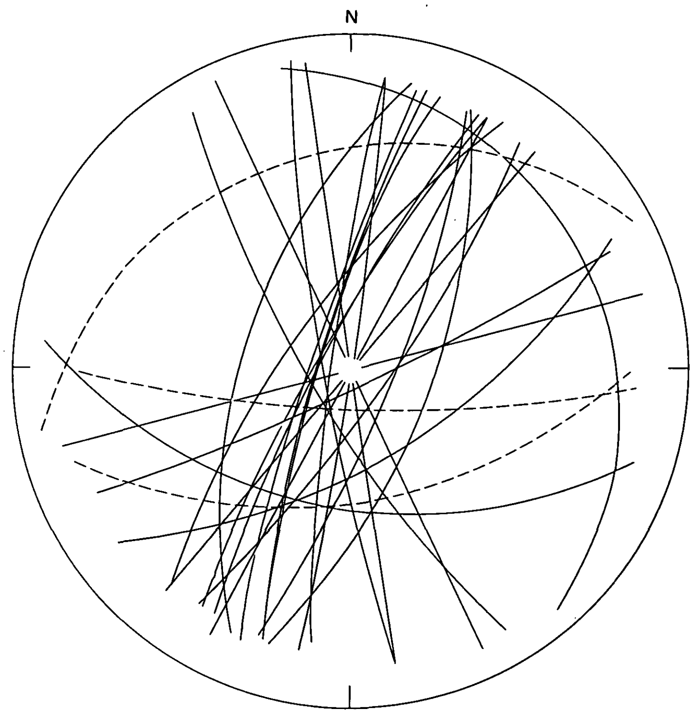


FIGURE 10.—Projections on a Wulff net of the principal joint sets observed at various localities in the Bald Eagle Mountain–Mount Massive study area. The dashed lines are the plots of observations taken within a zone below the sackung trenches believed to be subject to bulging, dilation, and rotation of blocks.

South Fork Fryingpan River, and on a north-trending ridge east of the river, informally here referred to as Surprise Ridge (figs. 2, 6). Trenches on the top and sides of both Mount Nast and Surprise Ridge trend roughly northward.

At Mount Nast, the most prevalent joint set appears to trend N. 10–25° W., with dips most commonly 77–87° SW., although some joints are vertical or dip steeply slightly northeast. The northwest trend is roughly parallel to most of the sackung trenches near the top and along the west side of the north-trending ridge south of Mount Nast (fig. 11). Joints and foliation were measured near the top of the ridge near the sackungen, north of the sackungen, and in a cirque at the head of Chapman Gulch near the south end of Nast ridge (fig. 12). Joints parallel to foliation are extremely variable, ranging from those that strike N. 35° W., dipping 28° NE., to others that strike N. 37° E., dipping 25° SE.

On Surprise Ridge, joints were measured on the ridge top near the center, at the north end, and in a cirque at the head of Granite Creek, between the two arms of Surprise Ridge, which bifurcates at its north end (fig. 6). Joints in the cirque are pronounced, and foliation is well developed.

The most prominent joint system, measured at several places on and near Surprise Ridge, is more variable in orientation than the major joint systems at Bald Eagle and Mount Nast. The sackungen trenches reflect this irregularity, as they are scattered profusely along the top of the ridge, criss-crossing in various directions, and give a general impression of shattering of the entire ridge top (figs. 13, 14, 15). The most consistent joint set, shown in figure 16, trends N. 5–25° E. and dips steeply either northwest or southeast. Foliation is variable, but, in general, it trends roughly east-west, with variations of 5–10° to the north or south.

At the north end of the ridge, small, but more consistently oriented, trenches trend northwest, in some places forming deep slots in the ridge top (fig. 17). The major joint trends are also more consistent, striking N. 10–44° W., dipping 64–84° SW.; others are N. 15–40° E., dipping 39–55° SE., and lesser sets dip and strike in various directions.

Joint spacing in the Mount Nast–Surprise Ridge area generally ranges from 8 in. to 3 ft with an average of

TABLE 1.—*Joint spacing at several localities in the Bald Eagle Mountain study area.*

[Most prominent joint set is underlined]

Location (localities shown in fig. 6)	Attitude of joint sets for which spacing was measured	Measurement of spacing of joint set in column 2 was made on joint surfaces with this orientation	Average spacing (inches)
On Hagerman Pass road, N. of Carlton Tunnel Portal, below Sta. 5	N. 5° W. 78° SW.	N. 88° W. 75° SW.	16.6
	N. 55° W. 42° NE.	N. 5° W. 78° SW.	12.7
Quarry on Busk Creek road, 1.8 mi NE. of Carlton Tunnel Portal	N. 28° E. 81° NW.	N. 83° E. 85° NW.	14.1
	N. 83° E. 85° NW.	N. 28° E. 81° NW.	23.3, 30.7
	N. 65° W. 25° NE.	N. 28° E. 81° NW.	16.5
Prominent outcrop south of farthest south switchback of trail from Busk Creek to top of ridge	N. 35° E. 70° NW.	N. 60° W. 42° NE.	12.0
	N. 45° W. 58° SW.	N. 35° E. 70° NW.	21.1
	N. 60° W. 42° NE.	N. 35° E. 70° NW.	31.5
At foot of cliffs below Sta. 3	N. 80-85° E. 75° SE.		18
Sta. B	N. 62° W. 45° SW.		12

about 18 in., although, as shown in figure 12, the average spacing locally may be much less than 1 ft.

JOINT ATTITUDES

Figures 18 and 19 show the poles of joints and foliation, and the projection of the principal joint sets, on Wulff nets, for observations in the Mount Nast-Surprise Ridge area, and illustrate the variability of orientation of the discontinuities. Although in limited areas the orientation appears to be consistent, in other areas, particularly near ridge crests, the orientations have no doubt been disturbed by sackung-type movements or possibly by frost action.

WILLIAMS FORK MOUNTAINS, COLORADO

In the Williams Fork Mountains north of Dillon (fig. 2), sackungen are abundant, from the south end of

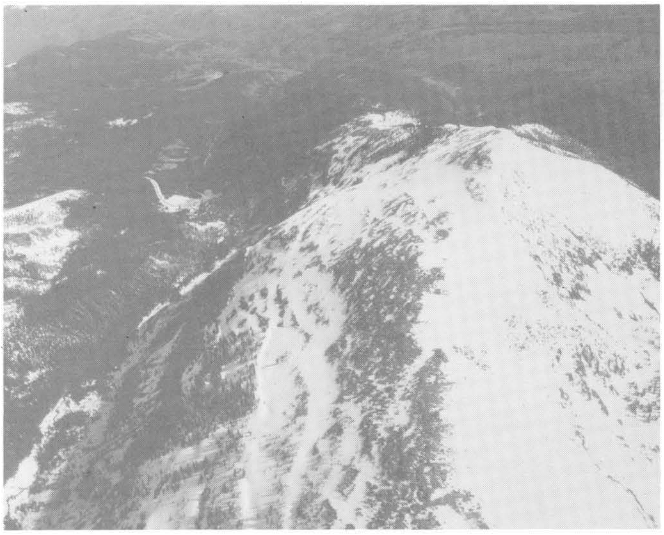


FIGURE 11.—Aerial view of Mount Nast, looking northward. In Chapman Gulch, on the west side of the ridge in the middle distance, is the northwest portal of the Mount Nast Tunnel, a part of the large Fryingpan-Arkansas transcontinental divide water-diversion project. The high western slope of Mount Nast shows numerous trenches, here filled with snow; whereas, the eastern slope appears to be less disturbed.

FIGURE 12.—View looking south at closely spaced joints trending N. 10° W. and dipping steeply west at the head of Chapman Gulch. The direction of Chapman Gulch closely parallels this joint system. Length of geologic hammer is 12.8 in.

the range, northward to Ute Peak (fig. 20). The area immediately to the west of Ute Peak has undergone major collapse, the movement being down and to the west (figs. 21, 22), with the formation of a ridge-top graben and many local scarps. A deep trench extending northwestward from Ute Peak, on the east side of the ridge summit, is shown in figure 23 and upward-facing scarps on the western slope are shown in figure 24.

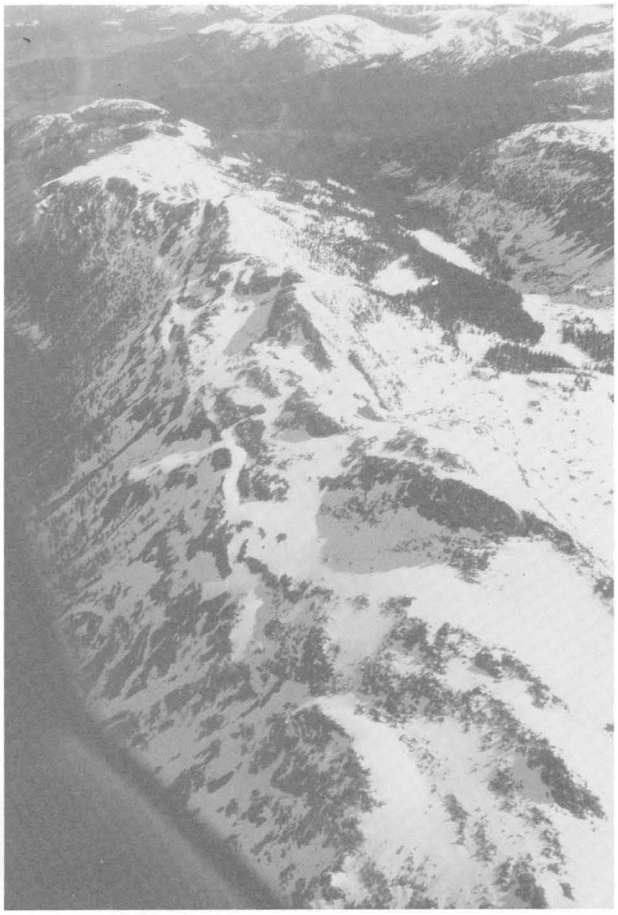


FIGURE 13.—Aerial oblique view looking northward along Surprise Ridge (whose summit at the north end is shown on the topographic base, figure 6, as South Fork No. 1). The cirque between the two forks of Surprise Ridge is on the right. The crest of the ridge is greatly disturbed. Trenches occur on both sides but are predominantly on the crest and western slope.

The geologists, who previous to this study mapped the Williams Fork Range, interpreted the disturbance just west of Ute Peak as a fault (fig. 20), and, indeed, it may be an old fault zone that was favorably oriented to control later sackung movements. There are, however, no marker beds in the Precambrian gneissic granite to use in positively identifying tectonic fault displacement.

One set of joints measured in migmatite on the low peak north of the deep trench ranges from N. 20° W., 65° NE. to N. 5° E., 46° SE.; other joints nearly normal to the first set trend N. 60–70° E., 50–85° SE., and one poorly defined set strikes N. 75–80° W. and dips 54–63° NE. The steep scarp on the west side of Ute Peak shows prominent vertical joints trending about N. 15° W.

For about 7.5 mi south along the crest of the Williams

(Continued on p. 13)

FIGURE 14.—Aerial oblique view looking north along the western side of Surprise Ridge. The eastward-dipping surface near the photograph center is a fresh-appearing, upward-facing sackung scarp.

FIGURE 15.—Trench on the east side of the crest of Surprise Ridge, looking north-northeast. Person on the snowfield in the trench indicates scale.

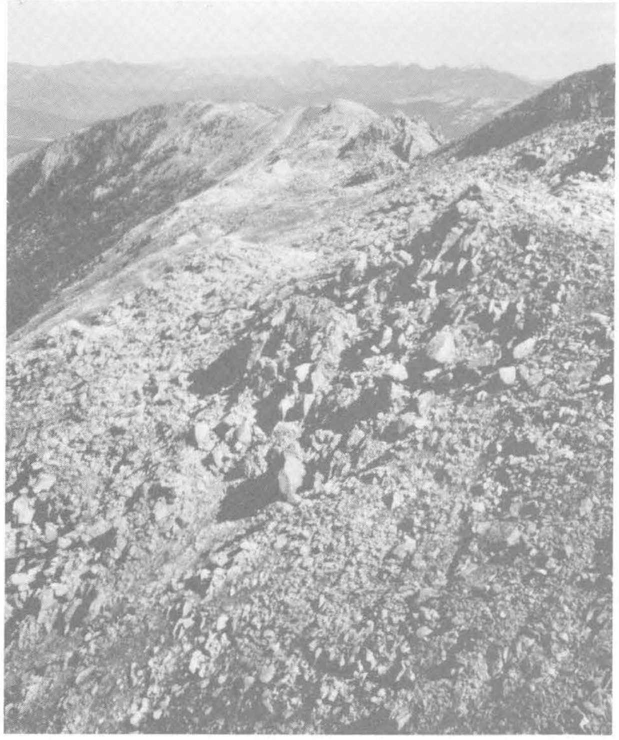


FIGURE 16.—Aerial oblique view looking northward of prominent joints on the west flank of Surprise Ridge that trend N. 5-25° E. and dip steeply westward.

FIGURE 17.—View looking northwestward along a slot-like trench on the crest of the north end of Surprise Ridge. Orientation is controlled by the major joint set.

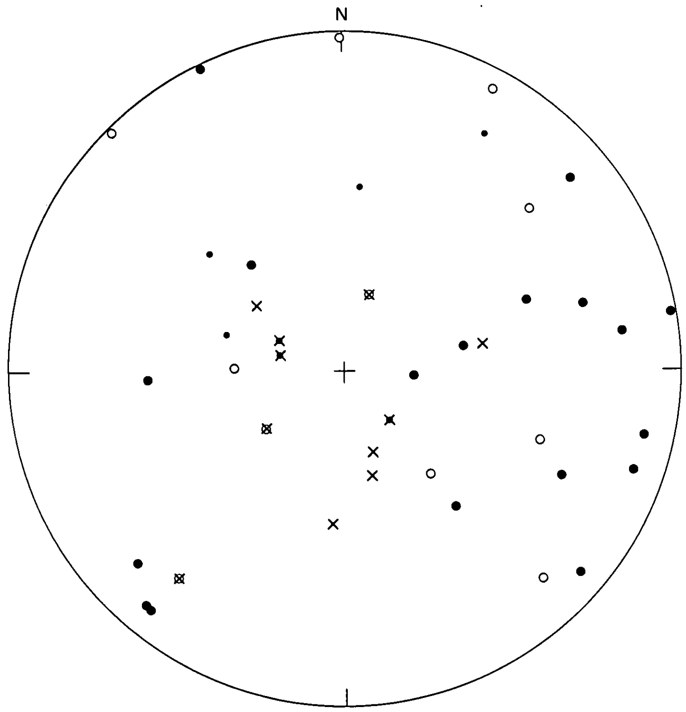


FIGURE 18.—Poles of joints and foliation observed in the Mount Nast-Surprise Ridge area, plotted on a Wulff net.

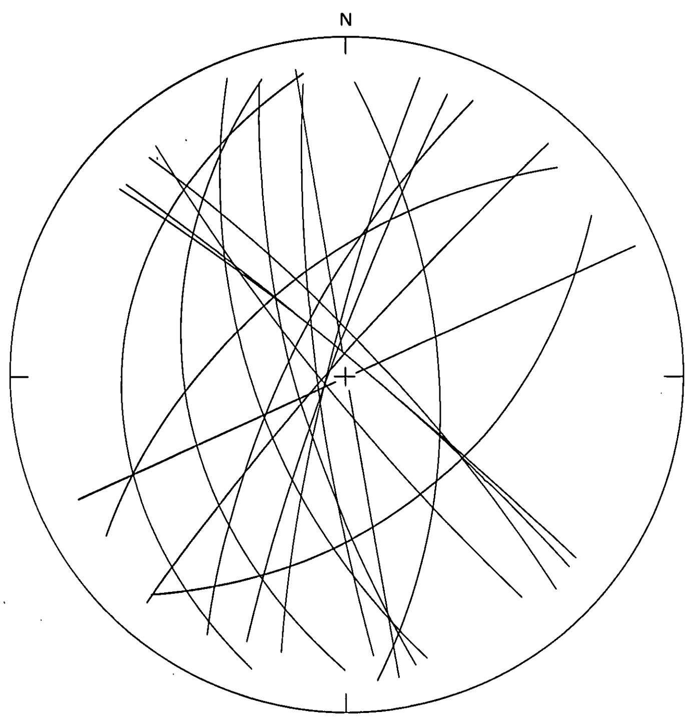


FIGURE 19.—Projections on a Wulff net of the sets of principal joints observed at various localities in the Mount Nast-Surprise Ridge study area.

Fork Mountains from Ute Peak to Ptarmigan Peak, there are many areas of ridge-top grabens and uphill-facing scarps, particularly on the west flank of the crest, as shown in figure 25.

The ridge extending eastward from Ptarmigan Peak has uphill-facing scarps on the south side and a well-developed ridge-crest graben. In this area, the most prominent joints strike N. 10-25° E., dip 79-83° SE., and follow the foliation in banded gneiss. Thus, the principal discontinuities cross the ridge at a high angle, yet the sackung features are parallel to the ridge, influenced not only by the the topography but perhaps, also, by secondary sets of joints that trend N. 65° E. to N. 78° W. and dip to the north.

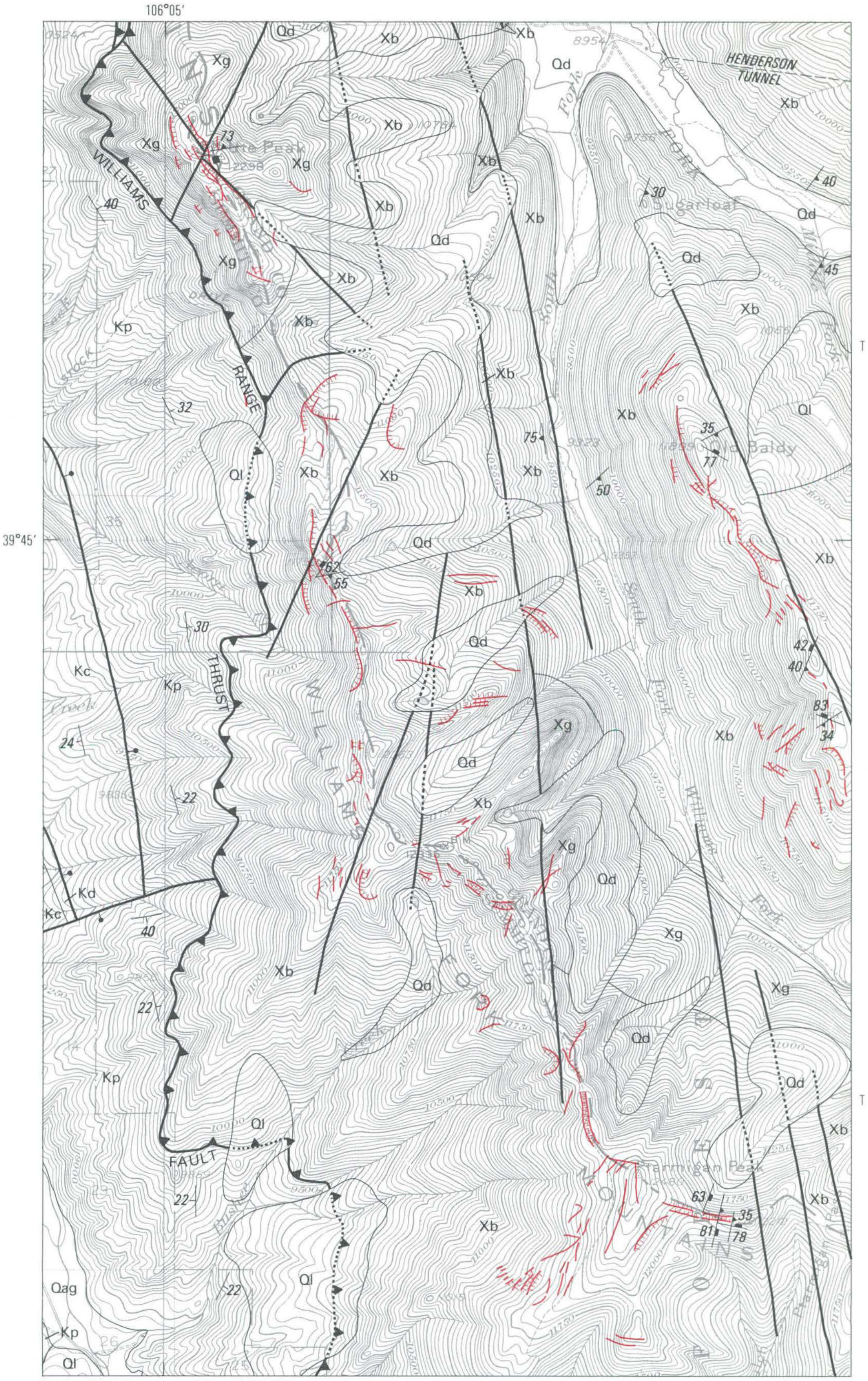
East of the main Ute Peak–Ptarmigan Peak ridge and separated from it by the South Fork of the Williams Fork is another ridge with conspicuous sackung features, especially for a mile or so south of Old Baldy (figs. 20 and 26). The most prominent joint system at Old Baldy trends N. 60–75° W. and dips 60–80° NE.; the trend is somewhat more westward than the most prominent trenches. Elsewhere on the ridge, the joints have various trends, although foliation in the gneiss fairly consistently strikes at a high angle across the ridge and dips 30–40° to the south.

The irregularity of joint systems, as observed along ridge crests in the Ute Peak–Ptarmigan Peak and Old Baldy area, is shown in the plot of poles of joints and foliation in figure 27.

SANGRE DE CRISTO MOUNTAINS, NEW MEXICO

In the Sangre de Cristo Mountains of northern New Mexico, sackungen have been observed in granitic rock on the peaks east of Taos and east of Costilla, near the border between Colorado and New Mexico (fig. 1). No obvious correlation could be established between jointing and sackungen in this area. Jointing, in general, appears to be somewhat irregular, rather than in prominent, well-defined sets.

(Continued on p. 18)



Base from U.S. Geological Survey, Dillion 1:62,500, 1929 and
Ute Peak 1:24,000, unedited advance print

R 77 W

EXPLANATION

QUATERNARY

Qag	Alluvium and stream gravels, bog deposits
Ql	Landslide deposits
Qd	Glacial drift
Qu	Non-glacial surficial deposits undivided

CRETACEOUS

Kp	Pierre Shale
Kc	Colorado Group—Niobrara Formation and Benton Shale
Kd	Dakota Sandstone

EARLY PROTEROZOIC

Xg	Granitic rocks of ≈1700 m.y. age group
Xb	Biotite gneiss and schist, migmatite

Contact

Fault—Dashed where approximately located, dotted where concealed. Bar and ball on downthrown side

Thrust fault—Sawteeth on upper plate

30 Strike and dip of beds

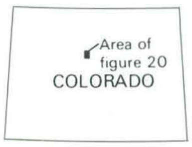
40 Strike and dip of foliation

Strike and dip of joint set

Vertical joint

Linear feature of probable gravitational origin

Scarp of gravitational origin—Teeth on downthrown side



LOCATION MAP

SCALE 1:62 500

1 ½ 0 1 MILE

1 .5 0 1 KILOMETER

CONTOUR INTERVAL 50 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

←FIGURE 20 (above and left).—Geologic map of the Ute Peak-Old Baldy study area, Williams Fork Mountains, Colorado, showing location of sackung-type features. Geology from Tweto (1973) and Tweto and Reed (1973b) with linear features and scarps of gravitational origin and some structural observations added by Varnes and Radbruch-Hall.

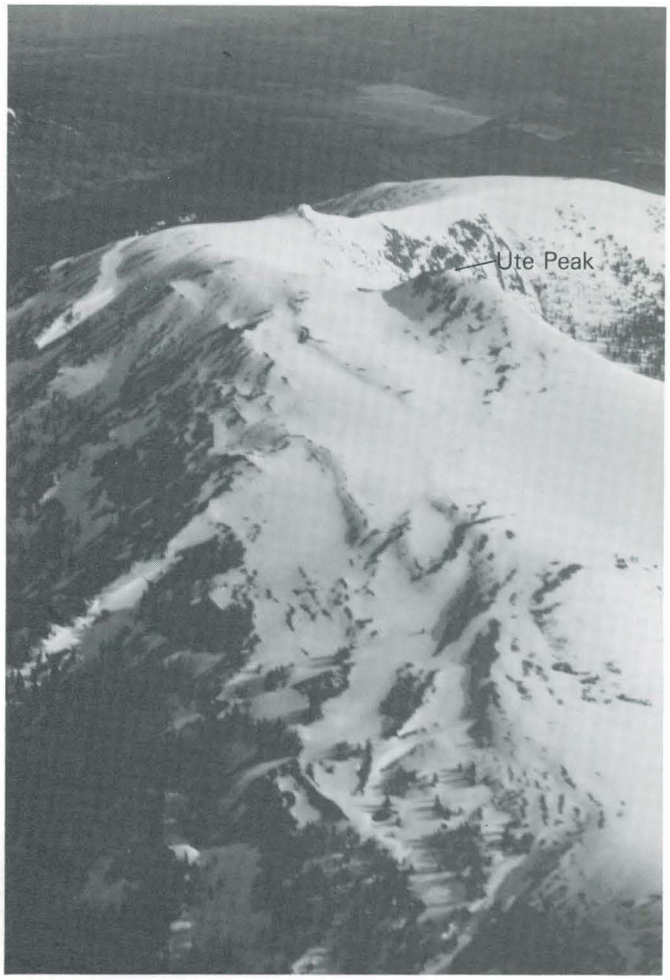


FIGURE 21.—Aerial oblique view looking northward toward Ute Peak, which is the short ridge that rises above the general summit area in the right-central part of the photograph. The west side of the ridge summit has moved downward and westward.

FIGURE 22.—Stereotriplet of the Ute Peak area showing a prominent southwestward-facing scarp northwest of Ute Peak on the east flank of the ridge, many scarps along the crest west of Ute Peak, and upward-facing scarps on the western slope.

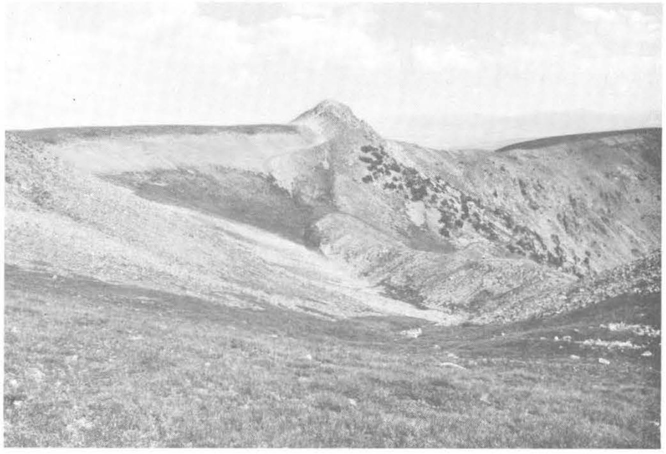


FIGURE 23.—View northward toward the trench extending northwestward from Ute Peak, which is out of view on the right. The scarp on the eastern side of the trench is about 30 ft high.

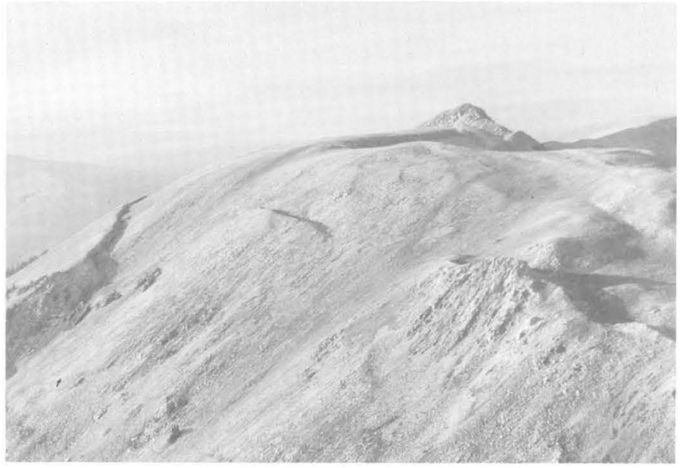


FIGURE 24.—Upward-facing scarps on the convex slope west and northwest of Ute Peak.

FIGURE 25.—Aerial oblique view looking east-southeast over prominent trenches on the western side of the rounded crest of the Williams Fork Mountains, 1.8 mi south of Ute Peak. The animals on the crest of the highest scarp are elk.

FIGURE 26.—Oblique aerial view looking north-northwest toward Old Baldy, showing trenches on the west side of the ridge crest; the larger trenches are outlined with snow.

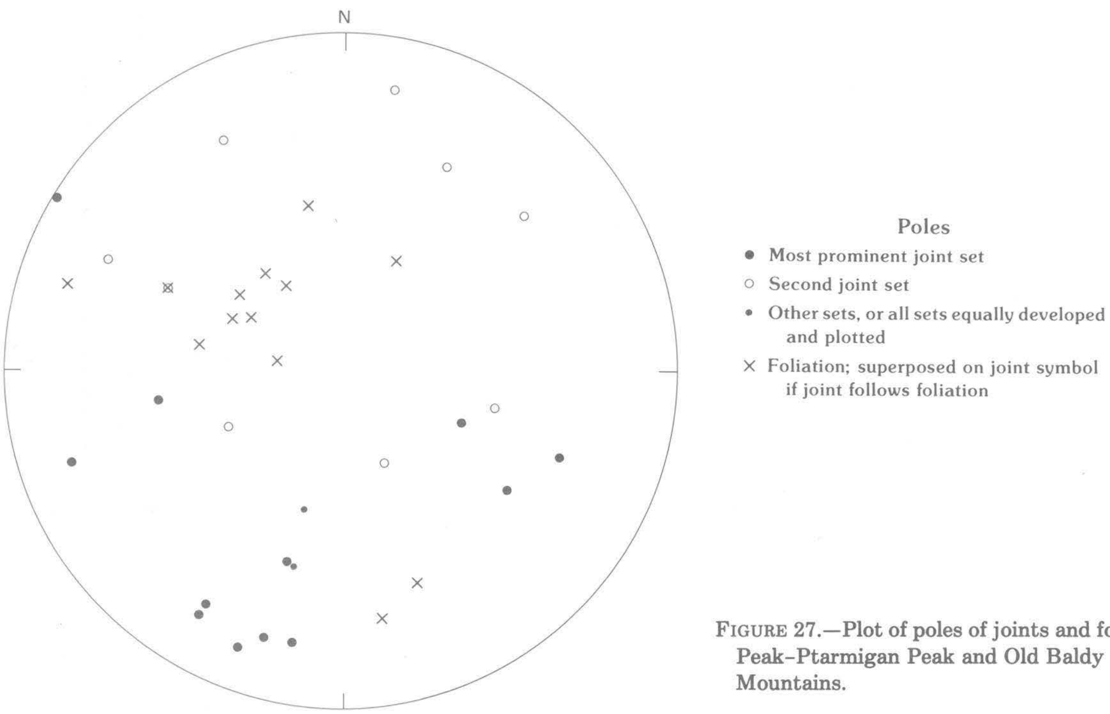


FIGURE 27.—Plot of poles of joints and foliation observed in the Ute Peak–Ptarmigan Peak and Old Baldy areas of the Williams Fork Mountains.

STILLWATER COMPLEX, MONTANA

In the Stillwater Complex, a large, basic, layered intrusive of Archean age in the Beartooth Mountains of Montana, sackungen have formed along the northeast side of the valley of the Boulder River, on the southwest side of a ridge known as Contact Mountain (Segerstrom and Carlson, 1982) (fig. 28). The main sackungen trenches and uphill-facing scarps strike approximately N. 65° W. and are about parallel to the slope contours (fig. 29). A major joint set parallels the layering, which strikes generally N. 60–65° W. and dips 50–60° NE. into the slope; another near-vertical set approximately normal to the layering strikes N. 30–35° E. (fig. 30). A graben lies at the crest of the ridge (fig. 31) and movement has taken place along both sets of joints to form the graben and trenches. Although the trenches are in bedrock, the ridges that bound them on the downhill side are capped in places by remnants of glacial till. Therefore, the sackung features formed after the glaciers that occupied the valley of Boulder River had retreated, which left the oversteepened slope unsupported.

RELATION OF SACKUNGEN TO TOPOGRAPHY AND ROCK STRUCTURE

TOPOGRAPHY

The primary control on the location of spreadings appears to be topographic; that is, the necessary relief to produce stresses sufficient to cause failure must be present, together with a sufficient length of free slope to allow their visible expression in shear surfaces. However, topography is not the sole determinant, for spreadings commonly are not continuous along ridges that have almost uniform shape and relief. Local and perhaps subtle variations in the spacing and orientation of pre-existing discontinuities, as well as minor topographic features, may then fix the limits of the area affected.

Although the relation of spreadings to topography is close, the orientation of ridges and the steepness of slopes of a mountainous area are themselves largely determined by the tectonic fabric of the region, as well as by factors that affected the accumulation of ice and distribution of glaciers during the Pleistocene. For example, the general northerly orientation of ridges in the Mount Nast–Bald Eagle study area (figs. 2, 6) appears related to regional joint and fault systems. These valleys were occupied by northward-flowing valley glaciers. Owing to predominantly westerly winds and to less direct exposure to afternoon sun, the accumulation of snow and ice was heaviest on the east or lee sides. Therefore, cirques on the higher slopes developed much more commonly on the east- and northeast-facing sides. The present ridges are asymmetric—steeper on the east and more rounded on the west. Gravitational spreading features are more commonly observed high on the west sides of these ridges than on the more deeply sculptured east sides. This may be due in part to greater remaining mass with resulting higher gravitational stresses on the west sides or, possibly, in part to removal of the features of gravitational spreading by erosion on the east sides.

MICROCRACKS AND JOINTS

In relatively homogeneous geologic terranes, sackungen appear to be related to joint systems that are the macroscopic equivalents of microscopic fractures in the rock.

A thin section of an oriented sample taken from the cirque southeast of Bald Eagle Mountain shows that the rock is cut by numerous microscopic open fractures, some of which cut across grain boundaries, some of which do not (fig. 32). The thin section was cut normal to the major joint set, which dips 73–85° SE., and strikes N. 47–67° E. At the point at which the oriented sample was taken for the thin section, the major joints strike N. 47° E. and dip 85° SE. (fig. 7). This orientation can be compared with the average N. 50° E. trend of the graben and hillside trenches on Bald Eagle Mountain. The thin section also intersects the foliation, which here strikes approximately N. 45° W. and dips 30° NE. Microscopic fractures in the thin section, parallel to the major joint system, cut across the foliation. Some of the fractures are partly filled with quartz, others are open.

A thin section, from an oriented sample taken from the face of the uphill-facing scarp on Mount Massive, was cut parallel to the secondary joint set, and across both the irregular foliation and the major joint set, which strikes N. 20° E. and dips 62° SE. The section was normal to the plane of the major joints. Foliation was indistinct in the section. Prominent microscopic fractures in the thin section were seen to be parallel to the major joints. Some fractures were seen to be wholly within individual grains; whereas, others were continuous across several grains.

FIGURE 28.—Southwest-facing slope of Contact Mountain, Stillwater Complex, Montana. Layering in the basic igneous rocks dips to the left (northeast) at angles of 50–60° into the slope. Some of the larger trenches are indicated by arrows. Total height of the slope is about 3,850 ft.

FIGURE 29.—Aerial oblique view of one of the principal uphill-facing scarps on the southwest slope of Contact Mountain, Montana, striking about parallel with the slope contour and dipping into the slope at the same inclination as layers within the intrusive body. The ridge on the downhill side of the trench in the lower center of the photograph is capped in places by remnants of glacial till.

FIGURE 30.—Joints in the layered intrusive rocks of the Stillwater Complex on Contact Mountain, Montana. The principal joints, which also control the direction of many sackung trenches and scarps, are parallel to the layering. Other well-developed joints, nearly vertical and nearly normal to the strike of the layering, appear in the background.

FIGURE 31.—Large graben on the crest of Contact Mountain. The long, high slope to Boulder Creek, shown in figure 28, is out of view to the left. Joint systems control the zig-zag direction of the principal failure surface on the right (northeast) side of the graben.

Another oriented sample was taken from the cirque between the two arms of Surprise Ridge; a thin section of the sample was cut normal to the vertical joints at the site, which trended N. 20° E. Microscopic fractures with the same orientation as the vertical joints (the major set) were clearly visible in the thin section.

The strike of the major joint system on Bald Eagle Mountain and in the cirque to the southwest is similar to the strike of the graben and trenches of the sackung mass. The displaced mass, to the southwest of Bald Eagle Mountain, consists of blocks of rock ranging from a few inches to several feet across. The rock mass that has bulged out into the canyon wall of Busk Creek consists of blocks that have moved individually, as indicated in figure 33, as well as in aggregates that form larger coherent units. Each larger unit has separated from its neighbor along the major joint planes that trend northeast about parallel to the contours on the slope, and that control the direction of the hillside trenches. Individual, smaller blocks apparently also separated along this joint set as well as along the other

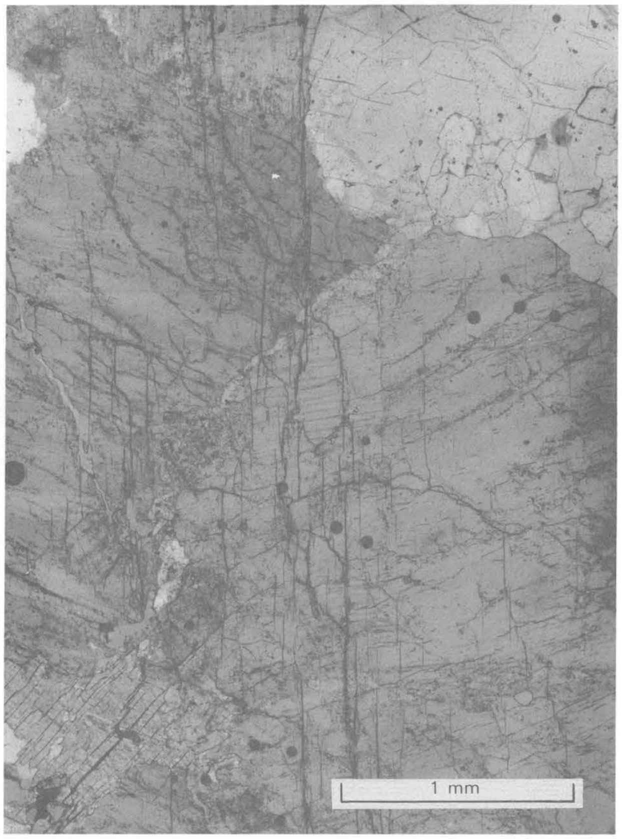


FIGURE 32.—Photomicrograph of thin section cut from oriented sample from the cirque southeast of Bald Eagle Mountain. The section is normal to the principal joint set, which is paralleled by the numerous microscopic fractures.

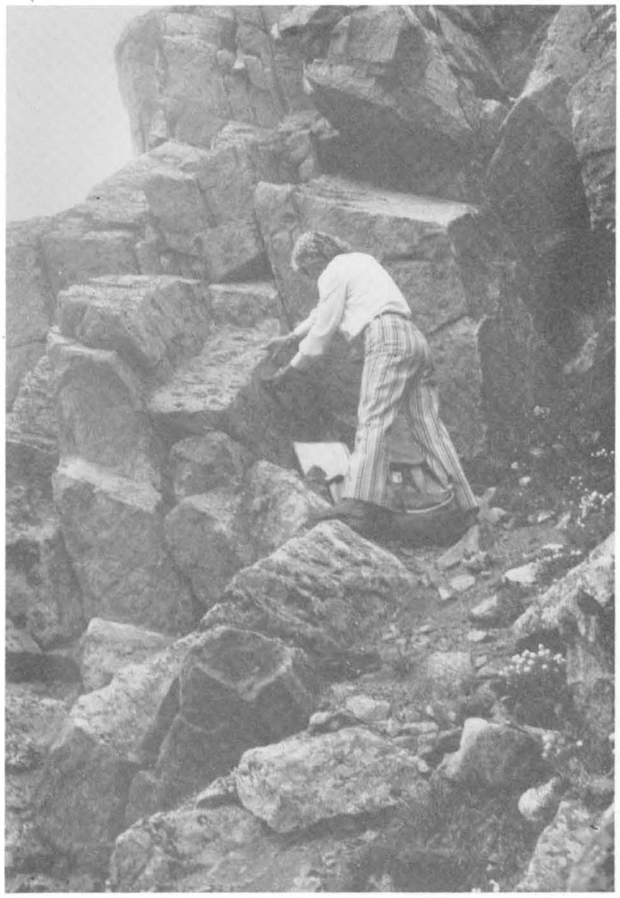


FIGURE 33.—Joint-bounded blocks in the lower part of the cliff below station 3 (fig. 6). This is in a zone of some rotation of individual blocks and probable dilation, although the mass itself has not yet fallen. The observation of principal joint direction, shown by dashed lines in figure 10, is different from the usual trend of principal joints away from the disturbed zone.

two sets, one of which is vertical and trends sub-normal to the major set (N. 24° W.), and one of which trends N. 45° W. and dips 30° NE., so that a component of the dip is outward toward the valley. Movement of individual blocks also can be seen in a quarry along the road below and northeast of the bulge of the sackung (fig. 34).

The direction of principal joints in the Bald Eagle Mountain-Mount Nast area has controlled the orientation of ridges and valleys developed during erosion by ice and water. Trenches and upward-facing scarps developed by gravitational spreading of ridges are usually more or less parallel to ridge axes and slope contours, and they also tend to make use of any zones of weakness, such as the principal joints. Thus, there is commonly a concurrent direction of ridge axes, contours, trenches and scarps, and principal joints. Moreover, other joint sets locally are well developed, so that rocks of the ridges are divided into blocks having dimensions of one or a few feet. At the scale of the mountain masses, the individual rigid units are much like grains in a small pile of sand a few feet high. In the mountain, the units are better interlocked, and, of course, they are subject to much higher gravitational forces; but the intimate division permits use of mathematical tools for analysis that are appropriate for particulate bodies, as is done in a later section.

FAULTS AND FAULT ZONES

Fault zones are usually intensely fractured and are weak; they are places where sackungen may be expected to occur. We have observed uphill-facing hillside scarps formed by gravitational movement along faults and fault zones in a few places. The principal scarps and graben at Ute Peak in the Williams Fork Mountains follows the course of a fault previously mapped by

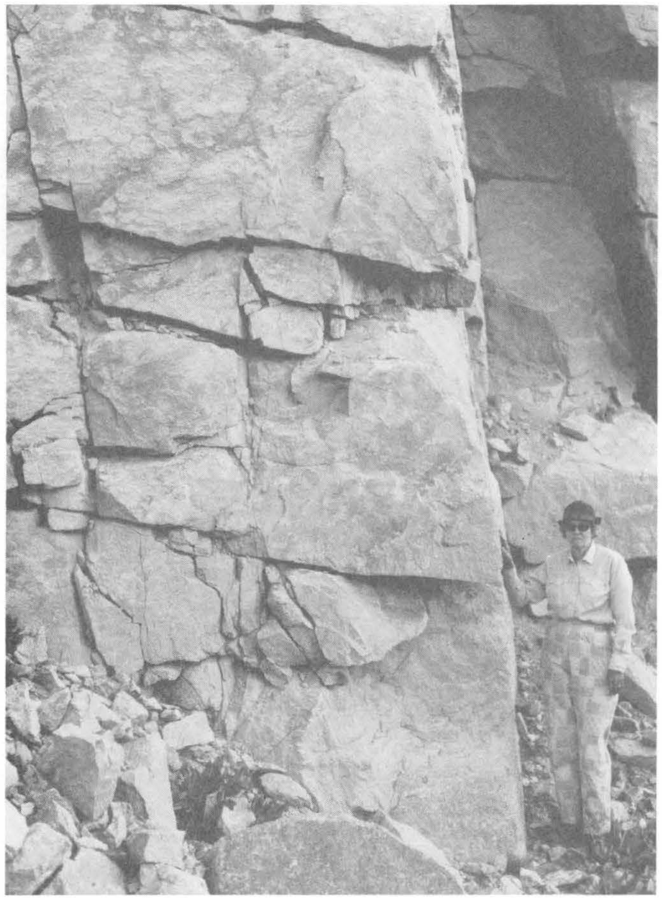


FIGURE 34.—Joint-bounded blocks in the quarry above the road in Busk Creek valley northeast of and below the principal area of trenches. Each large block has moved outward 1-4 in. relative to the block beneath on joints that dip at a low angle obliquely toward Busk Creek. This illustrates bulging movements on the lower slopes of the valley that are elsewhere obscured by colluvium and talus.

Tweto and Reed (1973b). Certainly, there is geomorphic evidence for either tectonic faulting or gravitational movement since the form of the mountain was established, but it is not known whether there is independent evidence for a tectonic fault. The scarp and trench on the northwest ridge of Mount Massive, which is definitely a gravitational-failure structure, was also previously mapped as a fault (Tweto and Reed, 1973a). Farther northwest of Mount Massive, on the ridge west of Pear Lake, Notch Lake, and Windsor Lake, there are also conspicuous uphill-facing scarps and grabens along a previously mapped fault (fig. 6). However, this structure may well be a fault that extends to some depth, because, beneath its northwest extension, an intensely fractured zone was encountered when driving the Charles H. Boustead tunnel, about 1,400 ft beneath the surface (fig. 6). Remedial work in the fracture zone delayed tunneling progress for nearly 11 months.

The east side of the valley of Busk Creek is marked by a prominent linear bench. Above the bench is a scarp or steep slope, approximately parallel to the contours through much of its course, that extends from well southwest of the sackung-affected area, northeastward nearly to the mouth of the valley of Busk Creek (figs. 4, 6, and 35). The trace of the bench on the surface is interrupted by rock-fall deposits below the sackung area, and the scarp in this area is unusually steep and high. This scarp may follow a zone of highly fractured rock, which may have had significant influence on the erosional development of Busk Creek valley by both water and ice, and thus on the topographic setting for the sackungen. The influence on the location of the sackung may have been more direct. The unusually high scarp below station 3 at the lower edge of the zone of trenches is on line with the projection of the bench and scarp on the slopes to the southwest and northeast, and provides a steep, free face toward which gravitational movements could occur.

Farther up Busk Creek valley, southwest of the well-developed sackungen, is an area with an unusual pattern of intersecting, shallow trenches that is about 0.6 mi north-northeast of Rainbow Lakes and on the slope above the southwest continuation of the bench and scarp along the southeast side of Busk Creek valley (figs. 36, 37). A few small, uphill-facing scarps do exist; this part of the slope may exhibit the initial stages of sackung development, before the well-jointed mass has formed into defined groups of failure units.

DIOBSUD RIDGE, WASHINGTON

A report on the Straight Creek fault zone in the Diobsud Ridge area of northern Washington State (McCleary and others, 1978), described uphill-facing scarps along a fault-line valley that marks the trend of the Straight Creek fault (fig. 38). A trench 5 ft in depth that was dug normal to one scarp and the depression immediately uphill from it revealed a zone of crushed and sheared rock in the depression that was interpreted to have formed by tectonic movement, although the trench showed very little that would conclusively identify the scarp as being of tectonic rather than gravitational origin. However, the presence of similar scarps on both sides of the fault-line valley strongly suggests that the scarps are gravitational, as the movement that formed them was downhill-side-up on both sides of the valley. This means that if the movement were tectonic, it would have been in opposite directions on opposite sides of the valley, which seems unlikely. The pattern of movement is, however, entirely consistent with gravitational movement along pre-existing weaknesses in the rock—in this locality, along a fault zone.

The study by McCleary and others (1978) included examination of aerial photographs covering 2,100 mi^2 of the North Cascades. Fifty sackunglike features were identified, of which 28 were confidently judged to be gravitational-spreading features. Of these, 19 were within a restricted zone 10 mi wide centered approximately on the Straight Creek fault zone, and the report concluded that the sackung features may have been triggered by active seismicity associated with the zone.

ELASTIC-PLASTIC STRESS ANALYSIS OF GRAVITATING RIDGES

Analytic studies of stresses in ridges and slopes by W. Z. Savage and his coworkers (Savage and others, 1985; Savage and Swolfs, 1986; Savage and Smith, 1986) have been applied to the problem of gravitational spreading of ridges with emphasis on the origin of uphill-facing scarps and ridge-crest grabens (Savage and Varnes, 1987). The analyses include an exact elastic solution for gravity-induced stresses in an isolated ridge of generalized parabolic cross section and a plastic solution for gravity-induced deformation of a slope yielding under the Coulomb criterion. These are appropriately combined to delimit regions of potential failure by plastic flow under given conditions of geometry and material properties.

The elastic solution by Savage and others (1985) for gravitational stresses in symmetric ridges is based on the Kolosov-Muskhelishvili (Muskhelishvili, 1953) method of complex potentials for plane elasticity. A conformal mapping function is used to transform an isolated symmetric ridge into a half-plane in which expressions are derived for gravity-induced stresses in the

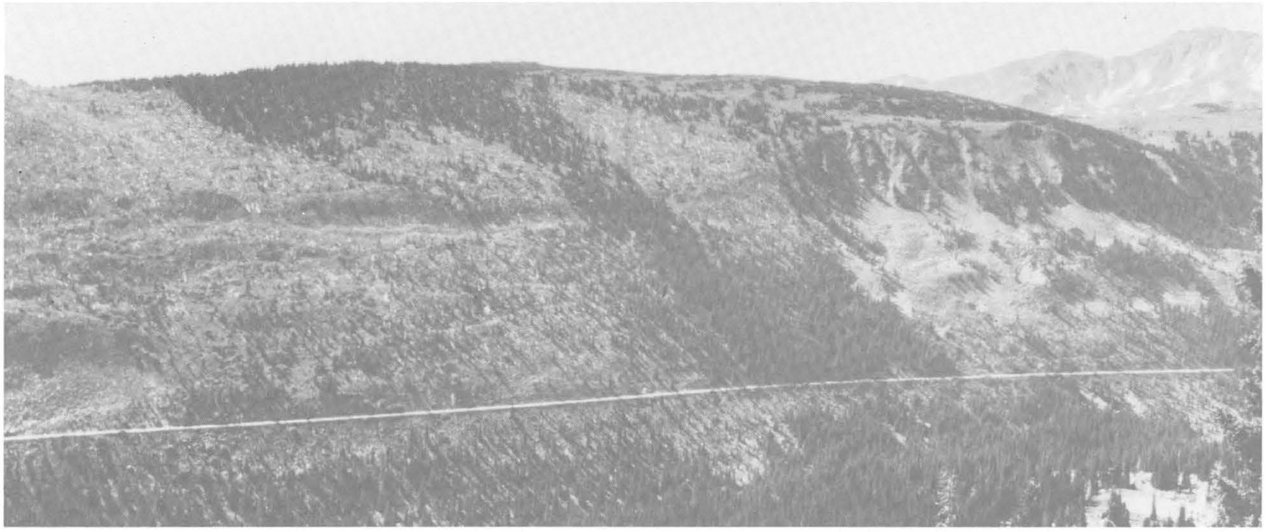


FIGURE 35.—View to the southeast over Busk Creek valley showing, on the right, the cliffs and rock-fall deposits below the area of sackung trenches. On the left, the prominent bench and low scarp continue to the northeast about halfway up the slope from the road.

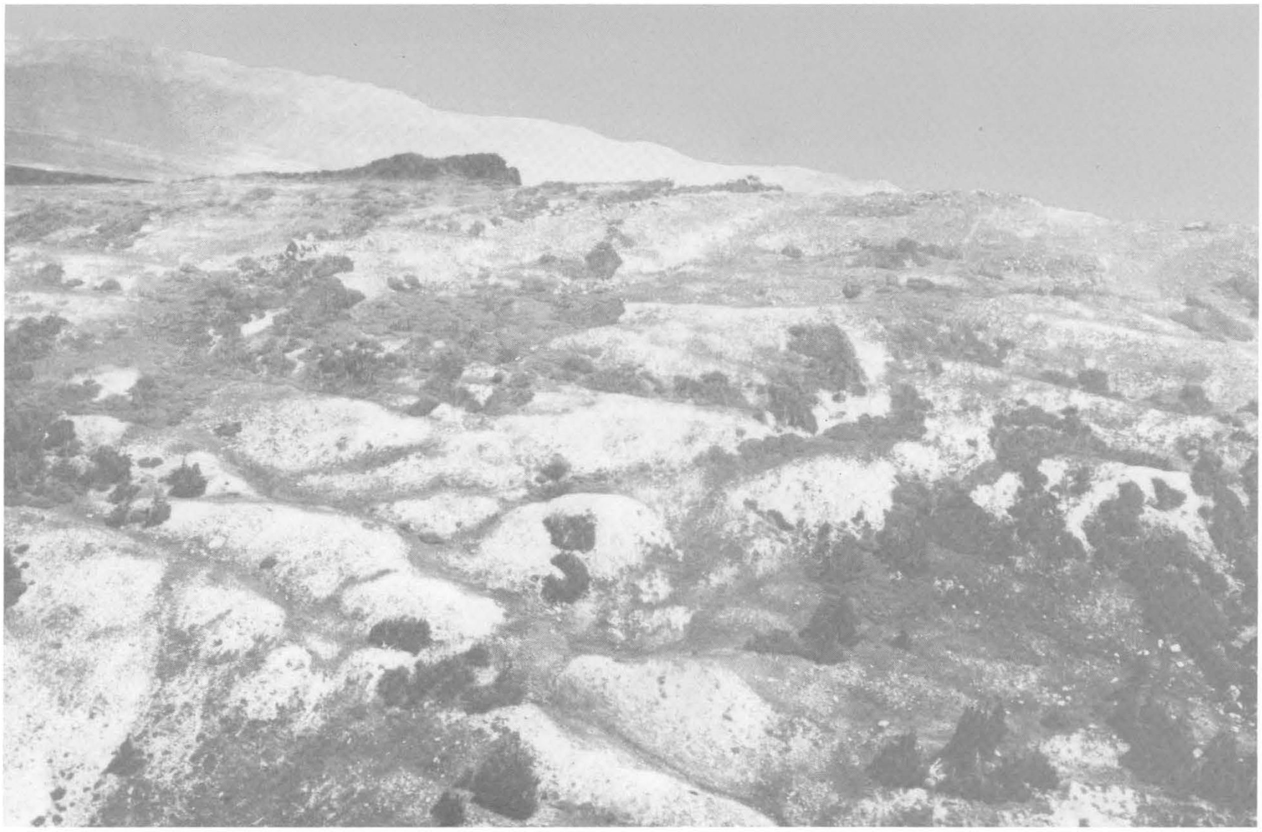


FIGURE 36.—Aerial oblique view of an area southeast of Busk Creek and southwest of the tributary valley that forms the southwestern border of the well-developed sackung trenches. This slope is in a similar topographic setting, just above the bench and scarp along the southeast side of Busk Creek valley. It may be in the initial stages of sackung development.

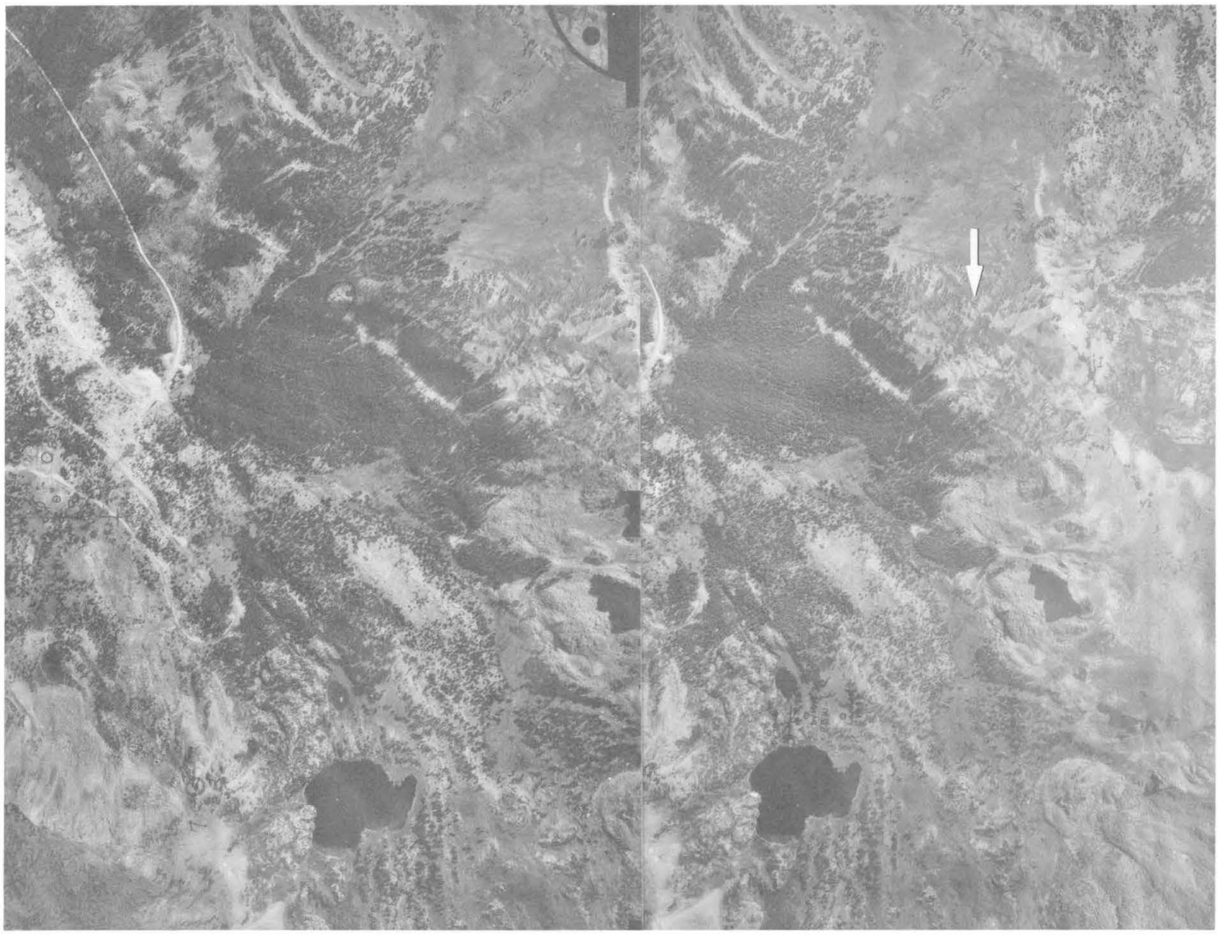


FIGURE 37.—Stereopair of vertical aerial photographs showing area of intricate pattern of shallow trenches (at arrow) above the prominent bench and scarp on the southeast side of Busk Creek valley. This area is in a topographic setting similar to that of the well-developed sackung across the tributary valley to the north, and may be in an earlier stage of development.

ridge (fig. 39). The mapping used to transform a symmetric ridge in x,y coordinates into a half-plane in u,v coordinates and the definition of the parameters a and b, which describe the shape of the ridge, are illustrated in figure 39. Specifically, a and b are parameters used in the conformal mapping where b is the ridge height and a + b/2 represents the x coordinate of the inflection point on the ridge flank.

Savage and others (1985) derived expressions for horizontal, σ_x, and vertical, σ_y, total normal stresses and shear stress, σ_{xy}, in and away from the ridge of the form

$$\sigma_x = \rho g b F_H(u, v, a, b, \nu) + \frac{\nu \rho g y}{1-\nu} \qquad (1)$$

$$\sigma_y = \rho g b F_V(u, v, a, b, \nu) + \rho g y \qquad (2)$$

$$\sigma_{xy} = \rho g b F_S(u, v, a, b, \nu) \qquad (3)$$

where ρ is the density, g is the gravitational acceleration, ν is Poisson's ratio, and F_H, F_V, and F_S are complex functions of u, v, a, b, and ν. Effective stresses σ_x' and σ_y' are defined as $\sigma_x' = \sigma_x - P$ and $\sigma_y' = \sigma_y - P$, where P is pore pressure. Stresses given by equations 1, 2, and 3 satisfy the conditions that shear and normal stresses are zero on the ridge surface and satisfy the condition of plane strain parallel to the ridge. The stress state away from the ridge is given by assuming vanishing far-field horizontal displacements, which requires that the stresses far from the ridge are $\sigma_x = \frac{\nu}{1-\nu} \rho g y$, $\sigma_y = \rho g y$, and $\sigma_{xy} = 0$.

Figure 40 shows contours of normalized effective stresses $\sigma_x'/\rho g b$, $\sigma_y'/\rho g b$, and $\sigma_{xy}'/\rho g b$ by the exact solution for a/b = 1, P = 0.0, and ν = 0.25. Note that by decreasing a for a given b, narrower and steeper ridges can be created.

The predicted magnitudes of gravity-induced stresses from point to point in idealized ridges of the type shown in figure 39 are then compared to stress levels necessary

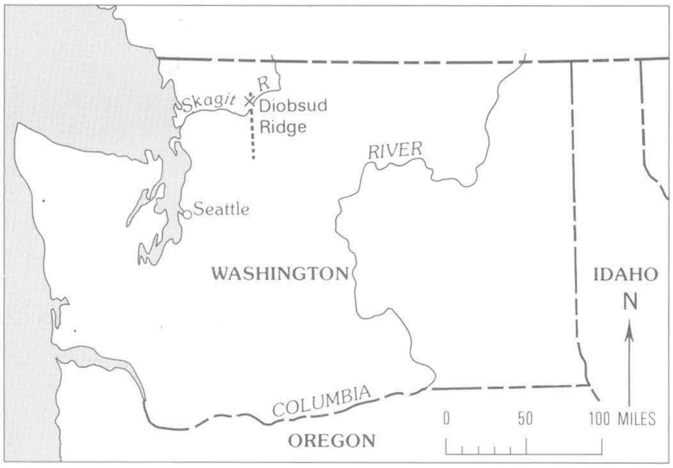


FIGURE 38.—Index map of the State of Washington showing location of the Skagit River, Diobsud Ridge, and, by dotted line, a part of the trend of the Straight Creek fault zone.

for yielding. The yield condition is that of Coulomb in the form given by Drucker and Prager (1952);

$$\sqrt{[(\sigma_x-\sigma_y)^2 + 4\sigma_{xy}{}^2]} = \sin\phi\,(\sigma_x' + \sigma_y' + 2c \cot\phi), \quad (4a)$$

or as

$$F = \frac{\sin\phi\,(\sigma_x'+\sigma_y'+2c\cot\phi)}{\sqrt{[(\sigma_x-\sigma_y)^2+4\sigma_{xy}{}^2]}} \quad (4b)$$

where ϕ is the angle of internal friction and c is the cohesion (resistance to shear) across a plane having zero normal stress.

In equation 4b, F represents the ratio of resisting shearing stresses (term in numerator) to maximum shearing stresses (term in denominator) at a point in the

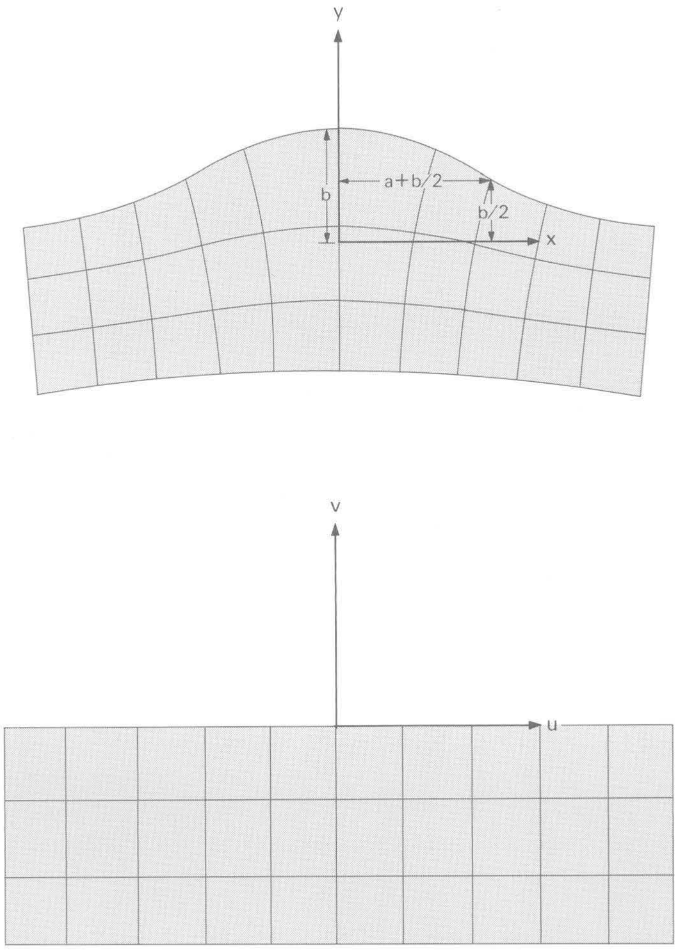


FIGURE 39.—Conformal transformation for a symmetric ridge in x,y coordinates to a half-plane in u,v coordinates and the definition of the parameters a and b which describe the shape of the ridge. Here, b represents the ridge height. When u=a and v=0, then x=a+(b/2) and y=b/2, which are the coordinates of the inflection point on the ridge flank.

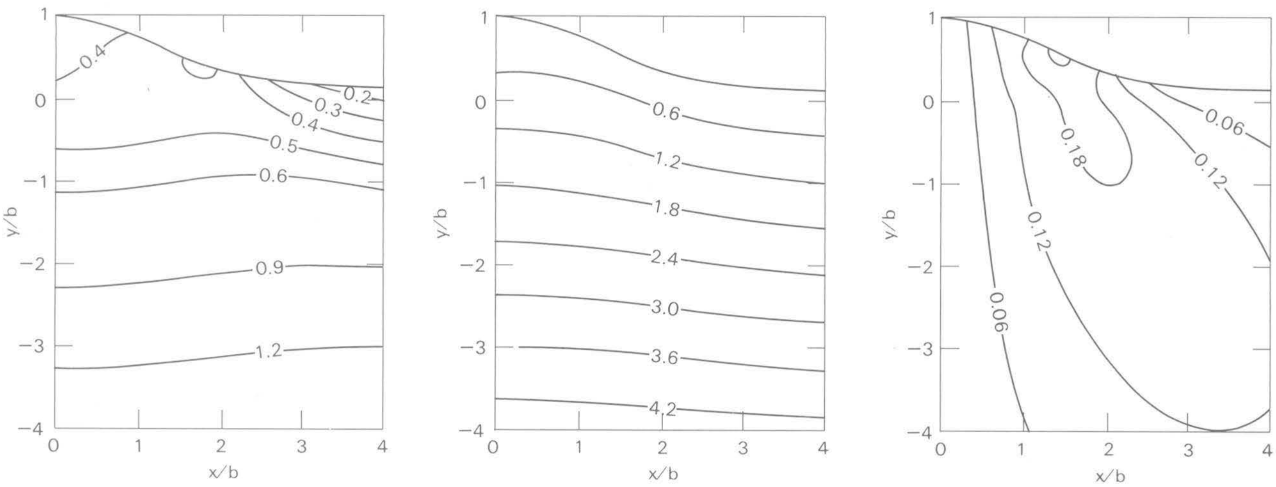


FIGURE 40.—Contour plots of $\sigma_x'/\rho gb$, $\sigma_y'/\rho gb$, and $\sigma_{xy}'/\rho gb$ from left to right, respectively, for a symmetric ridge where a/b = 1.0 and Poisson's ratio, ν = 1/4. Compressive stresses are taken to be positive and pore pressure is zero.

gravitating elastic body shown in figure 39. When F=1, the maximum shearing stresses on suitably oriented planes at this point is equal to the resisting shearing stress, and failure is imminent. When F>1, the resisting shear stress exceeds the maximum shear stress, and the material at the considered point is stable.

Some predicted failure zones, calculated by equations 1 through 4, for zero pore pressure and a few values of the parameters a, b, ν, ϕ, and c, are shown in figure 41. For simplicity, zero pore pressures are assumed, and because of symmetry, only the right half of the ridge is shown.

The depth to which the zone of potential instability of the slope extends is seen to depend not only on the steepness of the slope but also on the value assumed for cohesion (under conditions of zero pore-water pressure and angle of internal friction, $\phi=30°$) (fig. 41). The depth of the failure zone increases with steepness of the slope, markedly decreases with increasing cohesion, and can be shown (Savage and Smith, 1986) to increase with increasing pore-water pressure.

Plastic flow occurs in the failed region in response to gravity loading. Stresses in the failed region must satisfy the yield condition (equation 4), and the conditions of static force equilibrium. Also, velocities in the failed region must satisfy the continuity condition. Expressions for stresses and velocities that satisfy these conditions for a two-dimensional uniformly sloping half-space of Coulomb plastic material under elevated pore pressure and under gravity loading are given by Savage and Smith (1986).

Savage and Smith also give expressions for a system of coincident stress and velocity characteristics along which discontinuities in velocity are propagated through the plastically flowing mass. These characteristics are physically manifested as rupture surfaces.

The expressions for stress, velocity, and associated rupture surfaces given by Savage and Smith (1986) are exact only for uniformly sloping failed regions of constant thickness. However, these expressions apply approximately for failed regions of the type shown in figure 41, if the variation in depth of failure along the ridge flank is small and if the radius of curvature of the surface slope is large, compared with the failed thickness. Clearly, the approximations are poorest for steep slopes and best for gentle slopes.

A sketch of the predicted slip-line field in potential flow regions is shown in figure 42, which shows results of an analysis of a complete ridge with convex-upward slope at the upper part, a straight part or an inflection, and concave-upward lower valley wall. These three regions have different responses. The upper subregion is in extending flow, and the two complementary sets of potential rupture surfaces have opposite sense of shear. Uphill-facing surface scarps will develop along the steeply dipping set. More gently dipping downhill-facing scarps of the other set are possible but are commonly absent if the steep set is developed. Very often, the region of extension is preferentially developed or, at least, is more commonly preserved and easily observed than the lower region of compression in the lower valley wall. A subregion of plug flow may be present if the slope is long and planar. The subregion of compression in the concave part of the slope may have been removed by erosion in precipitous valley walls or may be obscured by colluvium, landslide debris, or talus. One should regard the basal surface forming an envelope to potential shear surfaces as a mathematical construction—the boundary between an elastic region below and a potentially failing region above.

The plastic-flow solution requires that in the subregion in extension an initial discontinuity on the steep set will propagate upward from the plastic-elastic

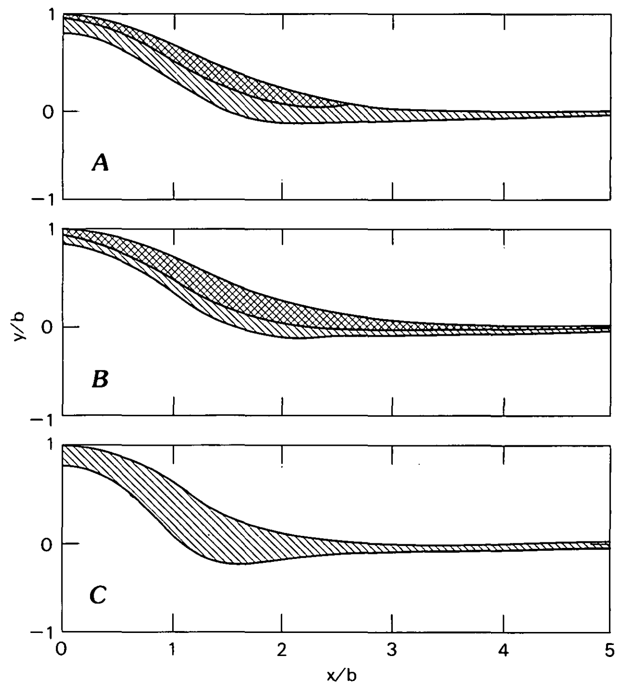


FIGURE 41.—Diagrams showing predicted zones of potential failure in a symmetric ridge for zero pore-water pressure and angle of internal friction $\phi=30°$. *A*, Shows the effect of cohesion, c, on depth of potential failure: cohesion is 0.01 in the diagonal-ruled case, 0.06 in the cross-hatched case. Cohesion is in units normalized with respect to ρgb (density × gravitational constant × slope height). *B*, Shows effect of Poisson's ratio: $\nu=0.35$ in diagonal-ruled area, $\nu=0.45$ in cross-hatched area. Cohesion is 0.01 in both cases. *C*, Shows effect of steeper slope; c=0.01, $\nu=0.35$. The x and y coordinates are normalized with respect to slope height, b (Savage and Varnes, 1987).

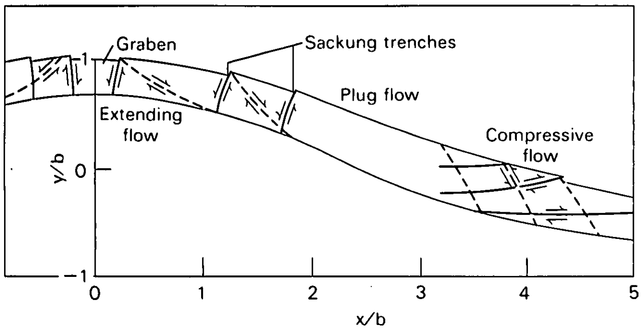


FIGURE 42.—Sketch of the potential flow regions and predicted senses of shear on examples of rupture surfaces for a symmetric gravitating ridge. Inactive rupture surfaces are dashed. The x and y coordinates are normalized with respect to slope height, b (Savage and Varnes, 1987).

boundary with exponentially increasing relative displacement toward the ground surface; the converse is true of the downhill-facing discontinuities. In the compressive-flow region, the opposite holds.

In summary, the principal contributions of the analysis toward an understanding of sackungen mechanics in homogeneous terranes are as follows:

1. The steeper the slope, the deeper the zone of potential instability.
2. Any significant cohesion drastically decreases the thickness of the failure zone.
3. Development of the set of uphill-facing scarps, complementary to the more usual downhill-facing scarps of conventional landslide, is not only possible but may be favored under the proper conditions of topography and rock structure. Preference for the uphill-facing scarp set suggests that the mountain has "solved" a least-work problem and has chosen to activate slip surfaces of the shorter set that extend to the free surface rather than longer surfaces that penetrate to increasing depth.
4. Increase in pore-water pressure increases the depth of the unstable zone.

CONCLUSIONS

Field observations in the Sawatch Range and the Williams Fork Mountains of Colorado, where the rocks are relatively homogeneous migmatites and granitic rocks or gneiss, show that the rocks involved in sackungen commonly move valleyward normal to major joint sets that strike approximately parallel to valley walls. Dips of the joints are variable and joints may dip steeply either into or out of the slope. The rocks are generally broken by minor joint sets and(or) planes of foliation that are more or less normal to the valley sides, as well as by joints or planes that are nearly flat or dip slightly valleyward, so that at least three sets of discontinuities commonly are involved.

Joint sets and other planes generally cannot be measured reliably within the sackungen, because the blocks composing the moving masses have rotated so that the original orientation of joints and foliation cannot be determined. Exposures are generally good and measurements reliable, however, in nearby glaciated areas above timberline in these high mountain regions, particularly in glacial cirques. Thin sections of samples of fresh rock taken where jointing and foliation can be measured show that microscopic fractures seen in thin section have an orientation similar to that of the open principal joints visible in the field and similar to that of the trenches characteristic of the sackungen in two areas.

Where gravitational sackung-type movement has taken place along tectonic shear zones, it may be difficult to ascertain whether the scarps are the result of tectonic activity or the result of gravitational movement that has used a previously existing zone of weakness, or both. Uphill-facing scarps in any seismically active area should be examined carefully, to attempt a determination of whether they are of gravitational or tectonic origin. A possible criterion for making this distinction is that scarps of gravitational origin are more likely to have their location, orientation, continuity, and sense of displacement determined by local topography than are fault scarps resulting from regional tectonic stresses.

Grabens and hillside trenches that have formed where bedding planes or other discontinuities dip into a slope may have formed by toppling, bending of beds, or spreading of a ridge. All these mechanisms have been suggested by various authors. An elastic-plastic analysis indicates that ridge-crest grabens and uphill-facing scarps may result from activation of the set of potential shear surfaces that are complementary to the usual surfaces of slump-type landslides.

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We owe much to Czechoslovakian geologists, who, for many years, have made excellent studies of gravitational spreading of ridges in their country. We are indebted, particularly, to Arnold Nemčok and Tibor Mahr, whose untimely deaths dealt a serious blow to sackung research, and to their colleagues Josef Malgot, Jaroslav Pašek, and Milan Matula. In our fieldwork in the Western United States, we have been helped at various times and for various periods by our coworkers Sigrid Asher-Bolinder, Robert Fleming, Kenneth Segerstrom, William K. Smith, and Katharine Varnes, and by field assistants Greg Twombly and Erik Shaw. Lastly, the special skills of helicopter pilots Burt Metcalf, Paul Kinsey, Marc Pasewalk, and Jim Innes enabled us to go wherever required and brought us back, often under difficult conditions.

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