CHAPTER 2-- GEOLOGY

This chapter describes the bedrock and Quaternary geology of Snodgrass Mountain, with special emphasis of landslides. Because the area had been mapped several times before, our first task was to compare the various maps.

2.1 Methods

2.1.1 Digitizing previous landslide mapping

During the winter of 2006-2007 we digitized the landslide mapping from all seven previous landslide studies (Table 2-1). These maps were georeferenced by International Alpine Design, Vail, CO, for use in our GIS, so we could visually compare the various maps.

Table 2-1. Previous studies in which landslides were mapped on Snodgrass Mountain.

Author	Date	Title	Map Scale	Remarks and Digitizing
Gaskill et al.	1967	Geologic map of the Oh-Be-Joyful quadrangle…	1:24,000	Published USGS color map; being digitized by IAD
Soule	1976	Geologic Hazards in the Crested Butte-Gunnison Area (9 quads)	Ca. 1:43,000	Polygons identical to those in Gaskill.
Gaskill et al.	1991	Geologic map of the Gothic quadrangle…	1:24,000	Published USGS color map; **see DIGITAL APPENDIX D2.1 on DVD-ROM only**
Resource Consultants and Engineers (RCE)	1995	Geologic Hazard Assessment and Mitigation Planning for Crested Butte Mountain Resort	1:6,000	Includes several large landslide deposits, and many small scarps; digitized by Pioneer Environmental in 1995
Irish	1996	Geologic Hazard Study Zones 3-A and 3-B Crested Butte Mountain Resort Expansion Area Snodgrass Mountain	1:12,000	Concludes that Chicken Bone, Slump Block, and toe of East Slide are not landslides; digitized by GEO-HAZ in 2006
Baum	1996	Slope Stability of Proposed Ski Facilities at the Southeast Side of Snodgrass Mountain	1:28,235	Confirms that Chicken Bone is not slide; maps limits of East Slide same as in RCE in lower part, but like Irish in upper part; defines Slump Block; digitized by GEO-HAZ in 2006; **see DIGITAL APPENDIX D2.2 on DVD-ROM only**
USFS	2006	Snodgrass Mountain Geologic Hazards and Assessment of Potential Effects of Ski Area Development on Slope Stability	1:9,600	Divides Snodgrass into 13 Geologic Hazard Units; digitized by IAD in 2006

2.1.2 Photogeologic mapping

We performed our own photogeologic mapping for this project, and digitized it into the same GIS as described above. The main set of aerial photographs used for Quaternary geologic mapping was natural color stereo airphotos taken in 2004 (Table 2-2), which were examined with an Abrams CB-1 portable stereoscope.

Table 2-2. Stereo aerial photographs used in this study. For scanned versions, see DIGITAL APPENDIX D2.3 of this report (DVD-ROM).

Year	Source/ color	Mission	Lines-frames	Scale
1950-51	USDA/ B&W	DKK	10-12 to 10-14 15-56 to 15-57	1:20,000
1962	USDA/ B&W	EJY	3-106 to 3-107 8-268 to 8-271	1:20,000
2004	UDSA/ color	3040706/ 227	14-2 to 14-3 15-2 to 15-3	1:21,600

As a check on the 2004 photos, we also examined the earliest airphotos taken in this part of the Gunnison National Forest (1950-51). These airphotos revealed much more detail of the ground surface, due to the sparser forest cover compared to 2004.

All geologic contacts were drawn on acetate overlays attached to the stereo airphotos. The overlays were then scanned and heads-up digitized in MapInfo. Resulting polygons were then manually adjusted to fit to the topography as represented by 5-ft contours, in order to remove the relief displacement in the overlays.

2.1.3 Field mapping techniques

Field checking was performed via foot traverses, with locations measured via a Garmin 12-channel handheld GPS receiver (accuracy 3-6 m).

2.1.3 Drilling

Drilling methods are described in chapter 6, Groundwater.

2.1.4 Trenching

The two trenches on the east slide were excavated in July 2007 with a John Deere 610 trackhoe. Each trench was configured in a double-bench cross-section, with vertical walls 5 feet high, and a 5 ft-wide bench on each side of the central slot. Geologic contacts were painted on the wall with spray paint, and then the logged wall was photographed to make a controlled photomosaic log.

2.2 Previous geological studies

There have been seven previous geologic studies of the Snodgrass area, which can be divided into two groups. The earlier group (1967-1991) includes general geologic mapping studies of 7.5' quadrangles (Gaskill et al., 1967, 1991 [DVD-ROM]) and a broad-brush geologic hazard study that covered eight 7.5' quadrangles in the Crested Butte-Gunnison area (Soule, 1976). The former 2 studies did not specifically focus on landslides, although landslide deposits and scarps are mapped at 1;24,000 on the Gothic and Oh-Be-Joyful quadrangles. The 1976 Soule study did focus on landslide hazards, but covered a large area of eight 7.5' quadrangles, so did not specifically target Snodgrass Mountain.

A later group of 4 studies (1995-2006) specifically addressed slope stability issues on Snodgrass Mountain, in relation to a ski area expansion proposed by CBMR. These studies concentrated on the landslide complex on the southeast slope of Snodgrass (Fig. 2-1).

The earliest of these studies (RCE, 1995) provided the largest-scale landslide mapping (scale 1:6,000). Many of the smaller scarps mapped by RCE do not appear on any maps from later workers. RCE named the East Slide (Fig. 2-1, 2-2) and identified it as the youngest and most problematic landslide within the proposed development, and proposed a mitigation scheme. However, RCE extended the East Slide all the way up to the summit of Snodgrass Mountain, and thus included slopes directly below the summit that were mapped as intact Tertiary porphyry by Gaskill et al. (1991).

Irish (1996) did not agree with the RCE mapping in several critical areas. First, Irish did not think the "Chicken Bone" meadow area (GHU 6, Fig. 2-2) was a landslide, and instead mapped it as glacial till that extended from the base of the East Facet (GHU 12, East Face, 10,360 ft) downslope to about 10,100 ft. In his interpretation, the latest Pleistocene glacier eroded along the base of the East Facet, although this would put the glacier limit some 400 ft higher than mapped by Gaskill et al. (1991). Second, Irish did not map the East Facet as part of the East Slide, instead following the interpretation of Gaskill et al. (1991) that it was mainly unfailed porphyry. Third, Irish concluded that the East Slide (GHUs 5A, 5B) was a "mudflow" that was only about 9 feet thick, underlain by in-situ Mancos Shale, rather than 40-50 ft thick as interpreted by RCE from their boreholes. Fourth, Irish did not map the southern 1/3 of the East Slide as a landslide, but mapped it as glacial till. Irish's East Slide had a toe at the linear scarp between the middle (our polygon 36) and lower (our polygon 34) parts of the East Slide, a location we trenched in this study. Fifth, Irish did not map the prominent hill at the base of the proposed development (GHU 2, Slump Block, Fig. 2-2) as a landslide, although it was included in the landslide complex mapped by Gaskill et al. (1991). Instead, he concluded that this hill was in-situ Mancos Shale thinly veneered with till, and in fact was "buttressing" the West Slide complex that lay upslope (GHU 1B, Lower West Slide). His "Base Hill" was later named the Slump Block by Baum (1996). Overall, Irish mapped a much smaller area as landslides than did RCE (1995).

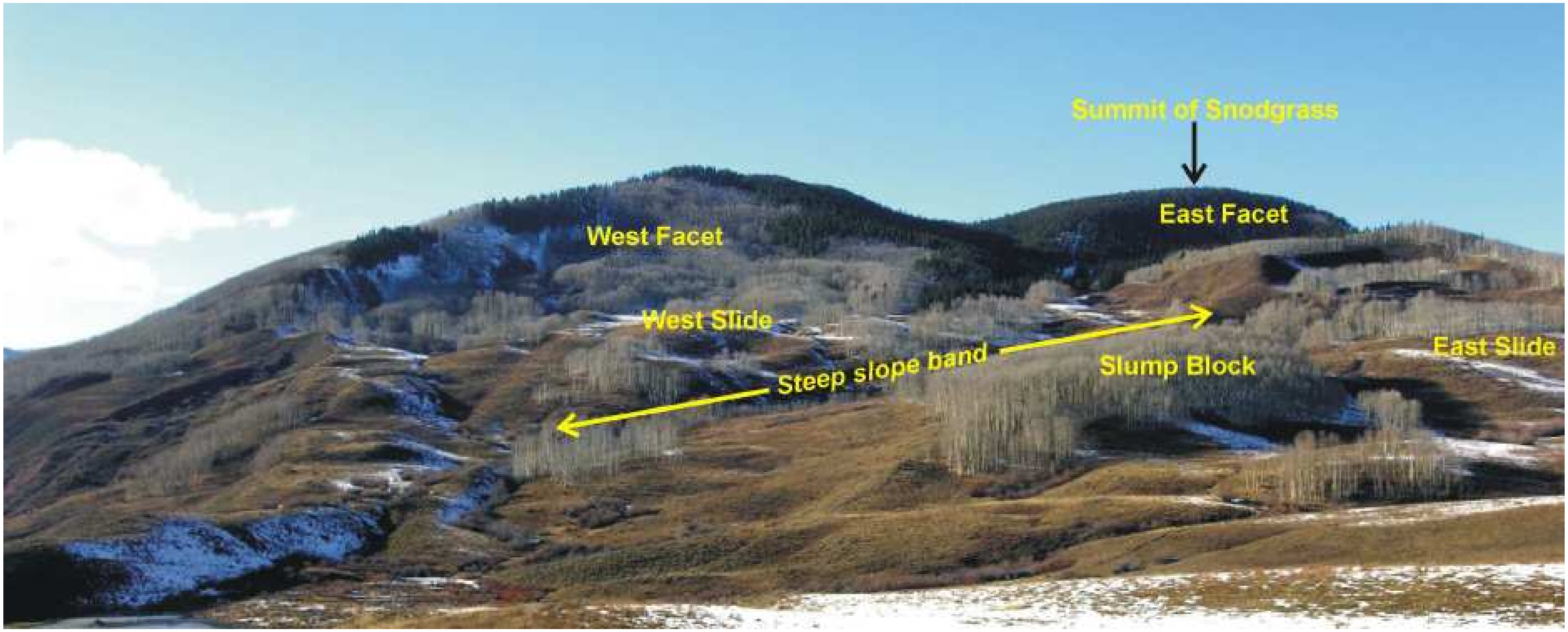


Fig. 2-1. Photo of the southeastern slope of Snodgrass Mountain, looking NW from Gothic Road. Labels indicate components of the complex mentioned in the text. The area in the foreground (bottom ¼ of photo) is private land, but all the rest shown in Forest Service land. Photo taken late in the day on Oct. 30, 2006.

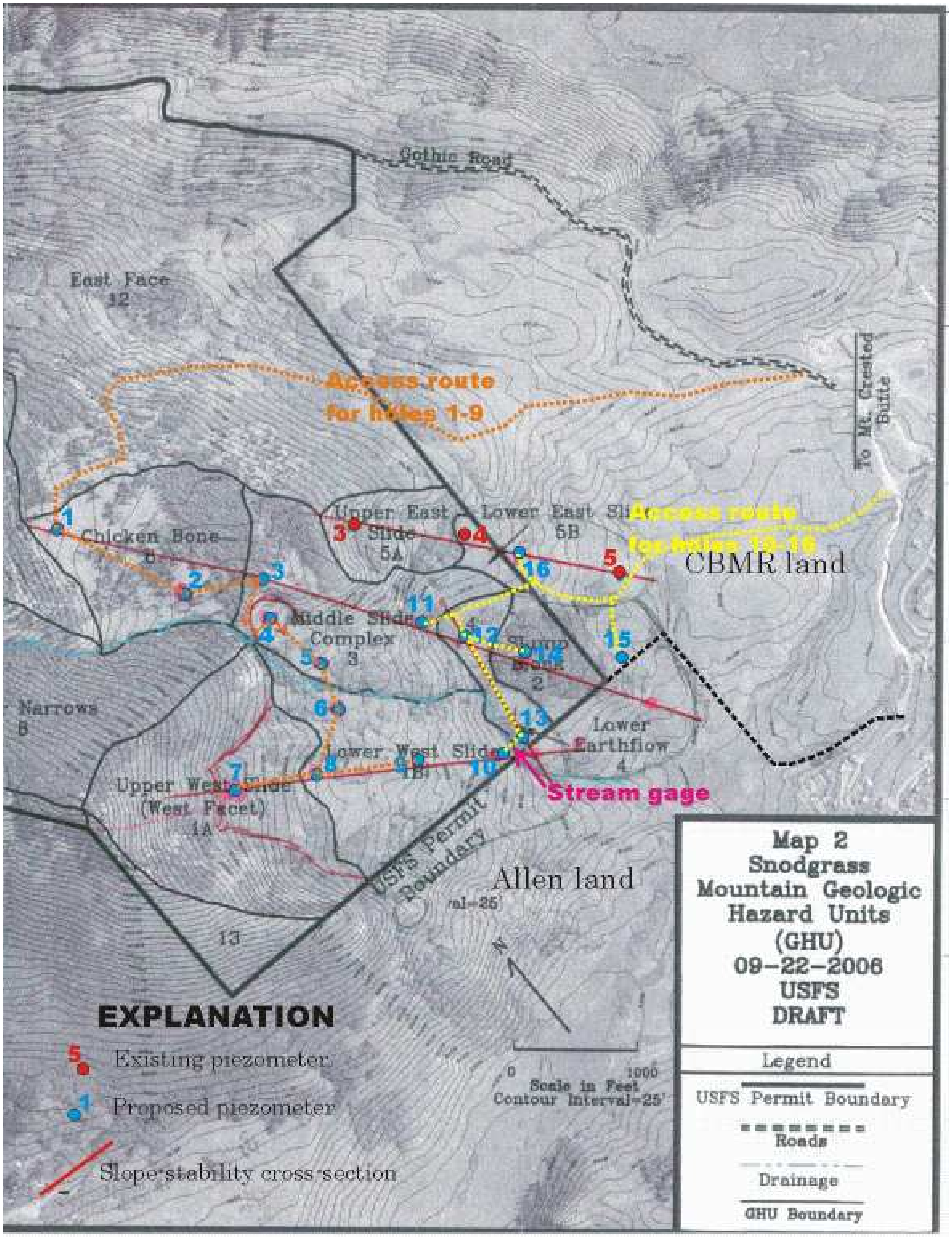


Figure 2-2. Location map of named sub-areas on the SE slope of Snodgrass Mountain. Map shows proposed monitoring wells, stream gage, access routes, and stability cross-sections. Black numbered polygons are USFS "geologic hazard units" from draft geologic hazards report on Snodgrass (Sept. 22, 2006), part of Map 2. Photograph in previous Figure was taken from the center right margin of this map (Gothic Road), looking toward the center left margin of this map (i.e., to the NW).

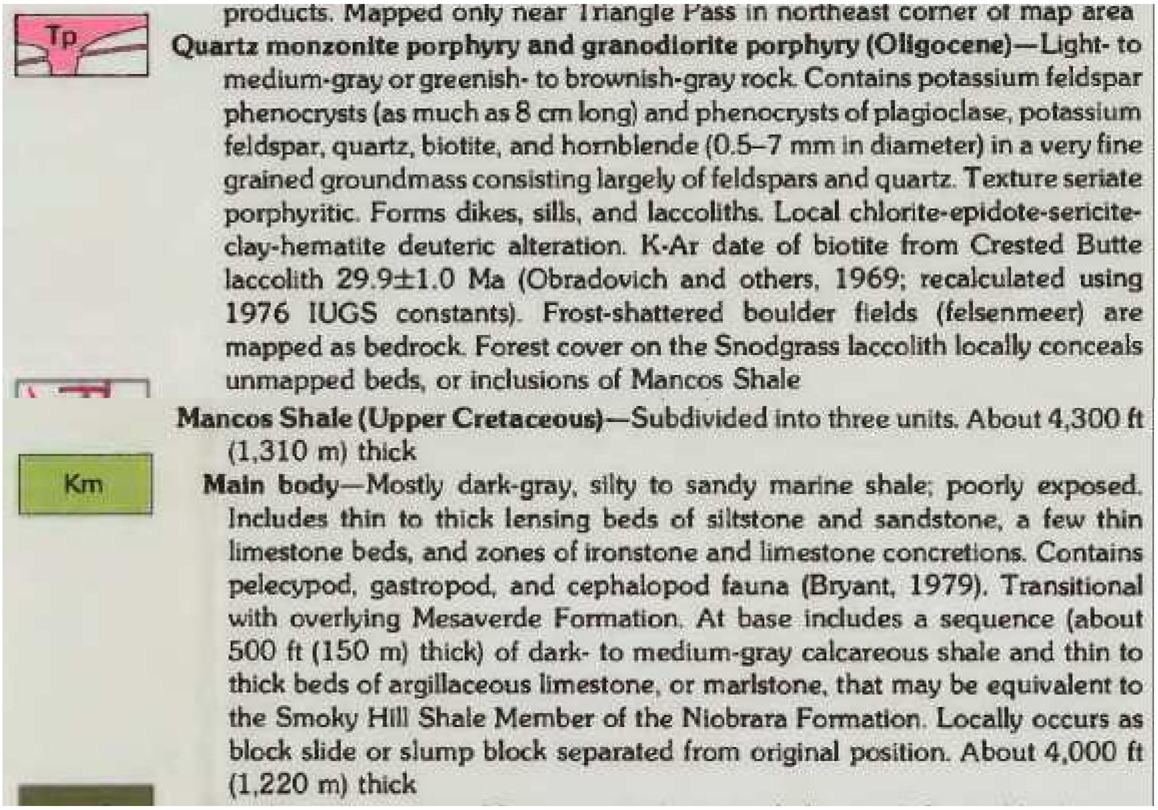
In order to resolve the discrepancies between the RCE (1995) and Irish (1996) reports, Rex Baum of the U.S. Geological Survey issued a third report (Baum, 1996; D2.2 on DVD-ROM). Baum agreed with Irish about the East Facet and the Chicken Bone area not being a landslide, but agreed with RCE that the southern 1/3 of the East Slide, and Irish's "Base Hill", were landslides. He termed the latter the Slump Block.

Finally, in Oct. 2006 GMUG issued a report entitled "*Snodgrass Mountain geologic hazards and assessment of potential effects of ski area development on slope stability*" (USFS, 2006). This report did not include any new mapping of individual landslide deposits. Instead, the authors divided the entire proposed development area into 13 "geologic hazard units" (GHUs) (Fig. 2-2). Within each GHU, the authors indicated whether any landslides had been observed within the GHU, and what types and ages of landslides they observed, if any. However, the authors did not show where such landslides were located within the GHU, nor did they give any indication of their size, or what percent of the GHU was composed of landslide deposits. They did assign an "age" of landslide movement to each GHU, but this "age" represented only the youngest evidence of movement they observed (or inferred) anywhere in the GHU, without reference to its location within the GHU or its spatial extent.

2.3 Bedrock Geologic Mapping

The author performed limited bedrock mapping in Sept.-Oct. 2006 and July, 2007, based on field observations while performing the Landslide Mapping (Section 2.3). Those observations confirm that the landslides and groundwater flow are controlled by the contact zone of the Tertiary porphyry over Mancos Shale, as explained below.

Mount Crested Butte, Snodgrass Mountain, and Gothic Mountain are all Tertiary laccoliths, formed by intrusion of granitic magma from the lower crust up into the Mancos Shale ca. 25 million years ago. During the intrusion process granitic magma forced its way straight upward in a semi-circular dike, until it reached a point several thousand feet below the earth's surface. At that point it began to lose momentum, and began pushing and flowing horizontally into the sedimentary rock layers. By prying apart sedimentary beds near the source dike, the flowing magma pushed radially away from the dike, eventually forming a mushroom-shaped intrusion or laccolith that domed up the Mancos Shale and overlying rock strata. The laccolith later cooled into solid rock (quartz monzonite porphyry; Fig. 2-3). After millions of years of erosion (mid to late Tertiary), the overlying uparched rock layers were eroded away, exposing the hard intrusive rock mass (Fig. 2-4). Continuing Quaternary erosion has proceeded to a much greater depth in the soft sedimentary rocks surrounding the laccoliths, which has left them as isolated mountains of hard Tertiary porphyry.



products. Mapped only near Triangle Pass in northeast corner of map area

Tp

Quartz monzonite porphyry and granodiorite porphyry (Oligocene)—Light- to medium-gray or greenish- to brownish-gray rock. Contains potassium feldspar phenocrysts (as much as 8 cm long) and phenocrysts of plagioclase, potassium feldspar, quartz, biotite, and hornblende (0.5–7 mm in diameter) in a very fine grained groundmass consisting largely of feldspars and quartz. Texture seriate porphyritic. Forms dikes, sills, and laccoliths. Local chlorite-epidote-sericite-clay-hematite deuteric alteration. K-Ar date of biotite from Crested Butte laccolith 29.9±1.0 Ma (Obradovich and others, 1969; recalculated using 1976 IUGS constants). Frost-shattered boulder fields (felsenmeer) are mapped as bedrock. Forest cover on the Snodgrass laccolith locally conceals unmapped beds, or inclusions of Mancos Shale

Mancos Shale (Upper Cretaceous)—Subdivided into three units. About 4,300 ft (1,310 m) thick

Km

Main body—Mostly dark-gray, silty to sandy marine shale; poorly exposed. Includes thin to thick lensing beds of siltstone and sandstone, a few thin limestone beds, and zones of ironstone and limestone concretions. Contains pelecypod, gastropod, and cephalopod fauna (Bryant, 1979). Transitional with overlying Mesaverde Formation. At base includes a sequence (about 500 ft (150 m) thick) of dark- to medium-gray calcareous shale and thin to thick beds of argillaceous limestone, or marlstone, that may be equivalent to the Smoky Hill Shale Member of the Niobrara Formation. Locally occurs as block slide or slump block separated from original position. About 4,000 ft (1,220 m) thick

Fig. 2-3. Description of the two bedrock units on Snodgrass Mountain, from Gaskill et al. (1991).

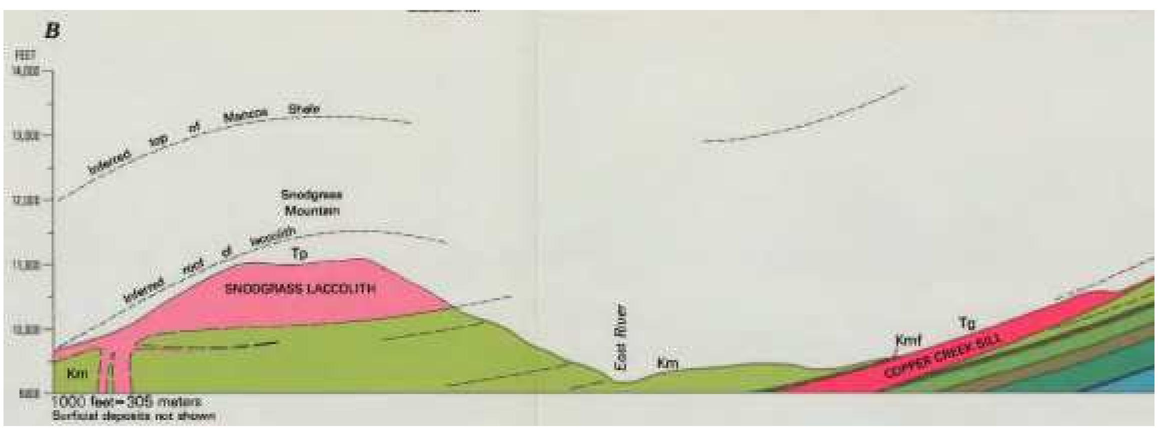


Fig. 2-4. Geologic cross-section through Snodgrass Mountain. This is the western half of cross-section B-B' of Gaskill (1991), which trends SW-NE. Note that beds in the Mancos Shale (Km) and thin sills in the transition zone are bent into a weak syncline below the laccolith.

According to the geologic map of the Gothic quadrangle (Gaskill et al., 1991; Fig. 2-5 of this report; also APPENDIX D2.1 on DVD-ROM), the contact between the bottom of the Crested Butte and Snodgrass laccolith, and the underlying Mancos Shale, is relatively simple. For the Mt. Crested Butte laccolith, Gaskill et al.'s cross-section E-E' shows a sharp contact with no thin sills of Tp beneath the

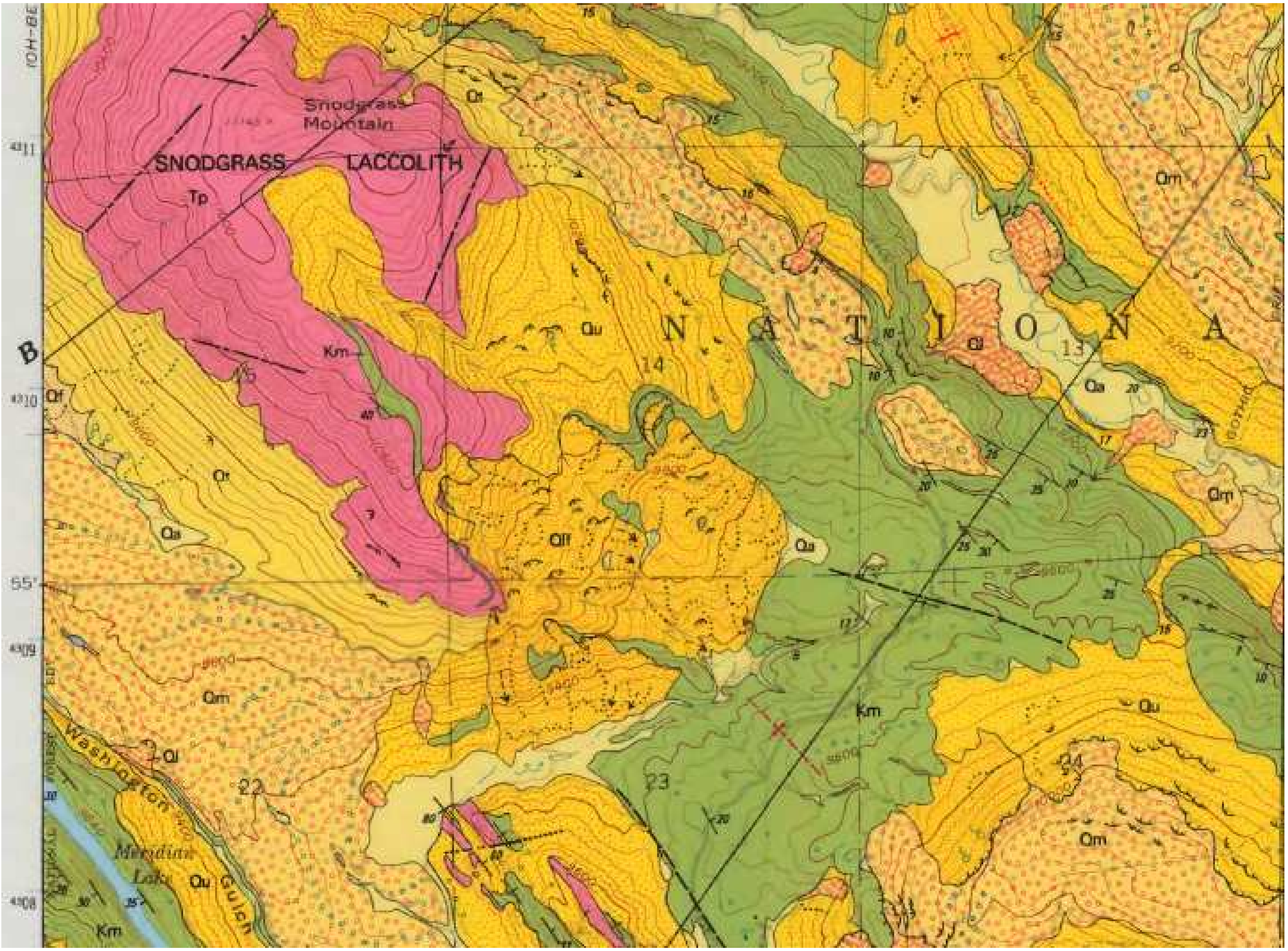


Fig. 2-5. Geologic map of the SE side of Snodgrass Mountain (from Gaskill et al., 1991). The two lines crossing from SW to NE are cross-sections B-B' (upper left) and C-C' (lower right). Along section C-C', beds in the Mancos Shale are folded into a NW-trending syncline that projects toward the center of the Snodgrass landslide complex (map unit Qlf). Strike-and-dip symbols indicate the syncline plunges about 10° to the SE, toward Mt. Crested Butte. For entire quadrangle map, see APPENDIX D2.1 on DVD-ROM.

bottom of the laccolith. For the Snodgrass laccolith, Gaskill et al.'s cross-section B'B' shows a single thin sill beneath the bottom of the laccolith. However, on the Geologic Map of the Oh-Be-Joyful quadrangle, Gaskill et al. (1967) show multiple thin sills beneath (and parallel to) the bottom of the Gothic laccolith. Such thin sills interlayered with thin beds of Mancos Shale beneath the laccolith form a "transition zone" that is critical in explaining the occurrence of landslides, as explained later.

The published USGS mapping thus implies that the transition zone increases in complexity and thickness from SE (Mt. Crested Butte) to NW (Gothic Mountain). This apparent increase may be real, or it may be an artifact of decreasing landslides from SE to NW. At Snodgrass Mountain and Mt. Crested Butte, most of the terrain flanking the laccoliths is obscured by landslide deposits, so it would be difficult to map thin sills of Tp interlayered with thin beds of Km, even if they existed. However, such an explanation does not affect the existence of larger bodies of Km within the laccolith, such as in GHU 8 at Snodgrass.

Detailed mapping by the author in two parts of the Snodgrass Mountain landslide complex suggests that the areas are underlain by thin sills of Tp interlayered with thin beds of Km. In the Chicken Bone area (GHU 6), the surface morphology is dominated by linear ridges and asymmetric swales trending in the downslope direction (Fig. 2-6). Float on the ridges suggests they are underlain by porphyry, in thin sills that strike NNW and dip WSW. Such a dip is compatible with the syncline described later. A second similar area is the SW face of Snodgrass Mountain that slopes down to Washington Gulch (see Sec. 2.5.4). Thus, I agree with Gaskill et al (1991), Irish (1996), and Baum (1996) that GHU 6 is not composed of landslide deposits except in small areas downslope of springs.

The SE slopes of Snodgrass contain several benches defined by more-or-less continuous outcrops of porphyry, even though all previous workers mapped the area as landslides. The largest bench lies between elevations of 9900-9950 ft (Fig. 2-7) and crosses the Lower West Slide (GHU 1B) and Middle SLIDE Complex (GHU 3). This bench crosses at least 6 mapped landslides, which suggests that it is not merely a coincidental alignment of 6 separate landslide toes. Instead, the implication is that the bench is underlain at a relatively shallow depth by a quasi-continuous sill of resistant porphyry in the transition zone. Geophysical data presented later also confirms high P-wave velocities (>10,000 fps) at relatively shallow depths. In these areas, and perhaps others not yet recognized, the hummocky surface topography is interpreted as a thin veneer of relatively fluid landslide deposits that have been draped over a bench-and-scarp topography, itself formed by differential erosion of sills versus Mancos Shale in the transition zone.

Fig. 2-6. Panoramic photograph of the Chicken Bone meadow area (GHU 6), taken from near its head. View to the SE. Meadow topography consists of asymmetric SE-trending ridges and swales, probably the result of differential erosion of SW-dipping, thin porphyry sills and intercalated beds of Mancos Shale. Compare this topography with the landslide topography shown in Fig. 2-1.This meadow occupies the top of the transition zone between the laccolith and the underlying massive Mancos Shale. The Mount Crested Butte laccolith is visible in center distance. Note the subdued low-angle topography of the lower half of the mountain (underlain by Mancos Shale and many small landslides) compared to the much steeper slopes on the laccolith proper.

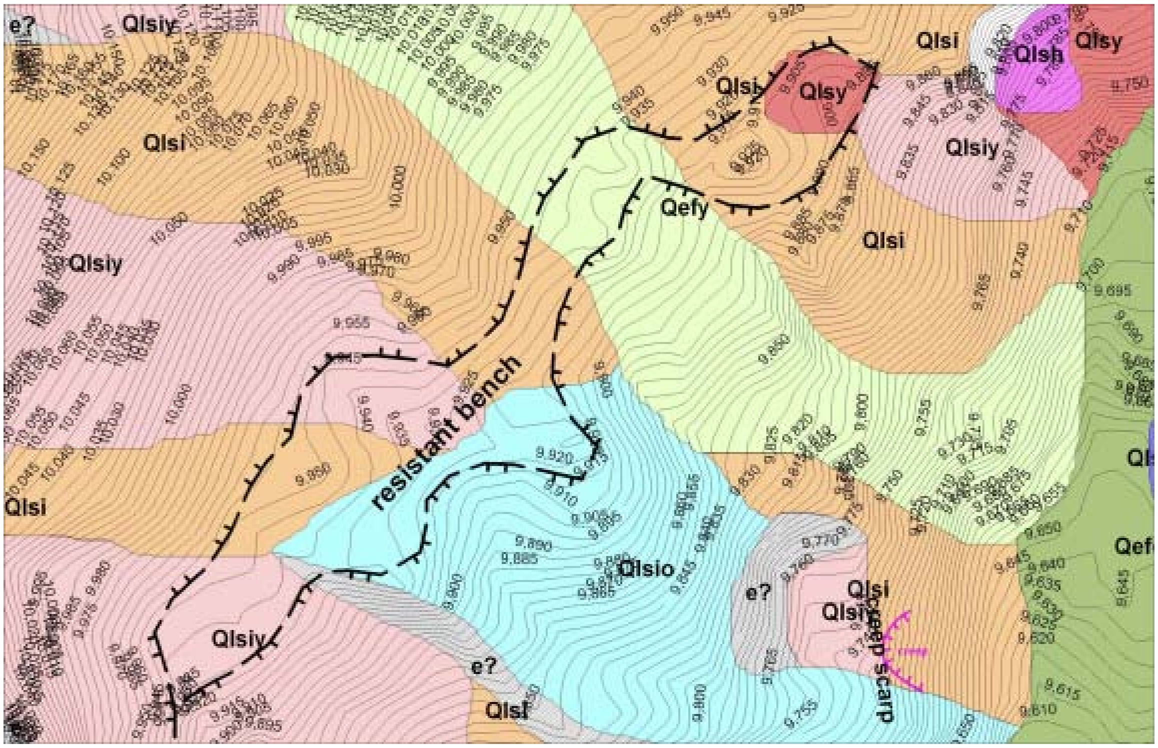


Fig. 2-7. Part of the landslide map showing the large resistant bench that crosses the Lower Western Slide (lower left) and Middle Slide Complex (upper right). North is at top. Landslide abbreviations: Qlsh, historic; Qlsy, young; Qlsiy, young-intermediate; Qlsi, intermediate; Qlsio; intermediate-old; Qlso, old; Qefy, young earthflow; Qefo, old earthflow.

In the vicinity of Snodgrass Mountain, strata of the Mancos Shale and other Mesozoic formations have been broadly folded. According to the Geologic Map of the Gothic quadrangle (Gaskill et al., 1991), the Mancos Shale beneath the town of Mt. Crested Butte has been folded into a gentle syncline that trends NW-SE and plunges gently (ca. 5-10°) to the SE (Fig. 2-5). According to cross-section B-B' on that same map, the Mancos Shale beds beneath the summit of Snodgrass Mountain are likewise folded into a gentle syncline (Fig. 2-4). We interpret this to mean that the syncline exposed at the surface in the town of Mt. Crested Butte continues to the NW beneath Snodgrass Mountain. If true, this means that the syncline passes beneath the landslide complex on the SE side of Snodgrass Mountain (Qlf on Fig. 2-5).

The final structural features of interest at Snodgrass Mountain are faults and lineaments. Gaskill et al. (1991) map 1 fault and 4 lineaments in the Snodgrass laccolith (Fig. 2-8). Three of these trend NE and two trend WNW. The only mapped fault juxtaposes Tp on its south (upthrown) side against Km on its north (downthrown) side, indicating the Km is part of the roof rock that originally overlay the laccolith. The southwestern projection of this fault is mapped as a lineament, which implies that some of the other 3 mapped lineaments may also be faults.

Finally, there is an inferred fault running NW-SE along the sharp western edge of the Snodgrass laccolith. This fault is shown at the surface only in one small area in the Gothic quadrangle (Fig. 2-5, bottom center), but regional maps (Fig. 2-8) show that the fault extends from south of Mt. Crested Butte to the southern part of the Marble quadrangle.

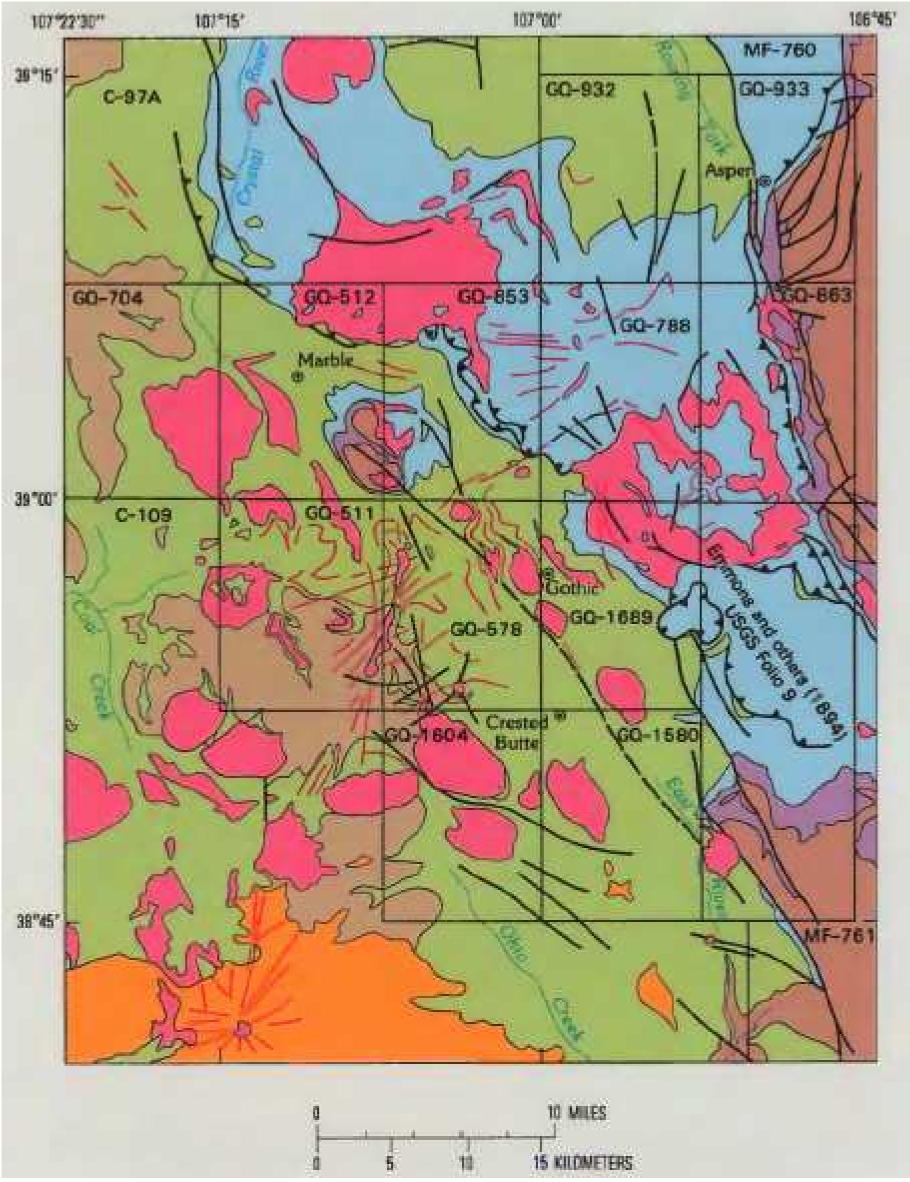


Fig. 2-8. Regional geologic setting of the Gothic quadrangle (right center, labeled GQ-1689). From Gaskill et al., 1991.

2.4 Quaternary Geologic Mapping

During the landslide mapping, we mapped several areas of non-landslide Quaternary deposits. Most of these deposits are correlative with non-landslide Quaternary deposits mapped by Gaskill et al. (1991) (Figs. 2-9, 2-10).

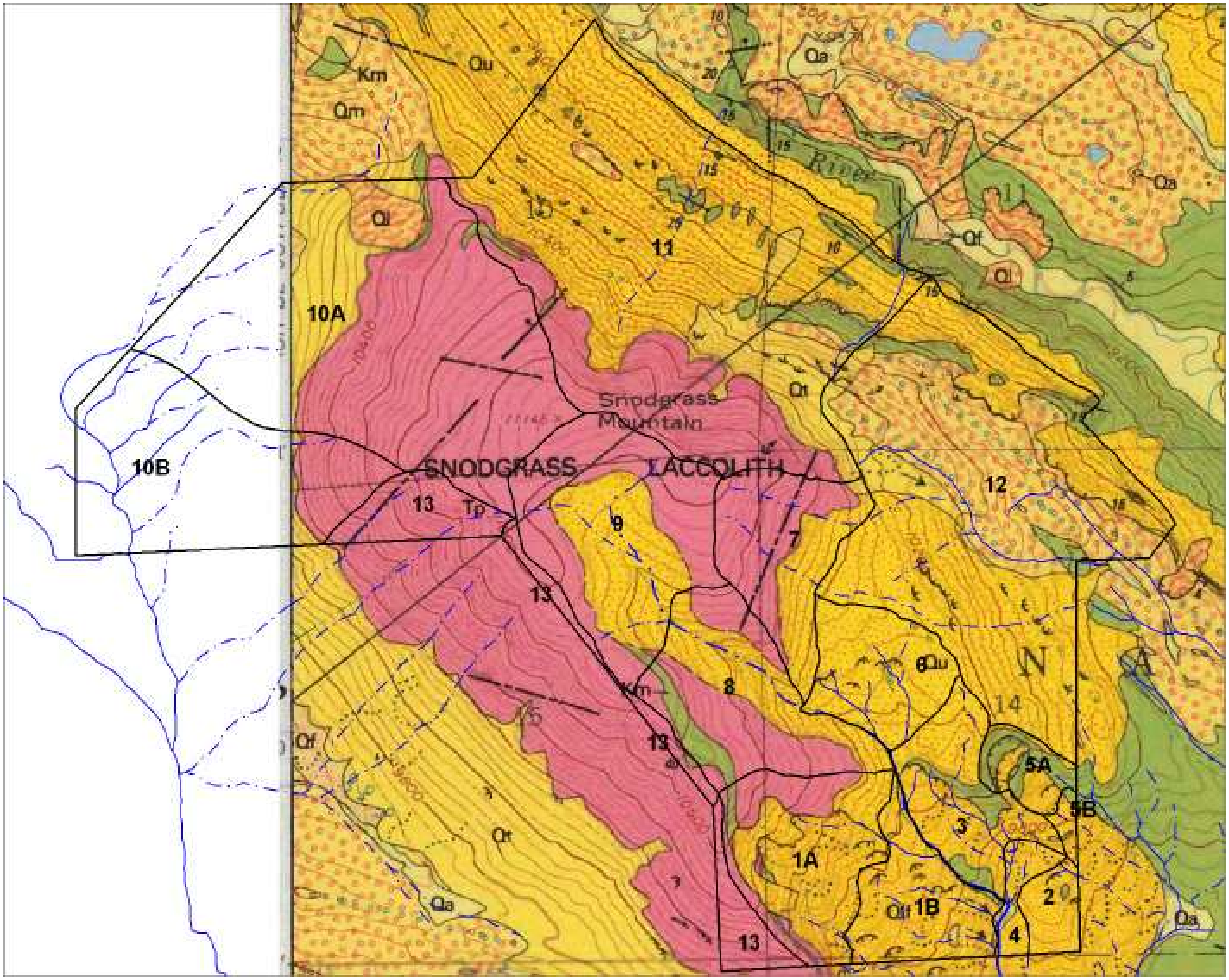


Fig. 2-9. Comparison of USGS geologic mapping of Gothic quadrangle (Gaskill et al., 1991) with GHUs defined by USFS (2006). GHUs 1A, 1B, 2, 3 (south half), 4, 5A, and 5B were mapped as landslide complexes. See text for details.

DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

Qa — **Alluvial deposits (Holocene)**—Unconsolidated stream deposits of silt, sand, and gravel. Includes organic debris, soil, and hydrous iron oxides in pond, swamp, and poorly drained fluvial environments, and glaciofluvial and lake deposits in major river valleys

Qf — **Alluvial fan and debris-flow deposits (Holocene)**—Generally poorly sorted silt- to boulder-size debris at mouth of tributary streams and gulches

Qdf — **Debris-flow deposits (Holocene)**—Silt- to boulder-size debris deposited by flood runoff in small drainage basins

Qt — **Talus (Holocene)**—Angular rock fragments forming talus cones, talus aprons, scree, talus streams, and colluvium-covered slopes. Locally includes protalus ramparts and extensive vegetated talus fields

Ql — **Landslide deposits, undifferentiated (Holocene)**—Many are shown only by landslide or slump-scarp symbols within other map units

Qlf — **Landslide, slump, debris-flow, and earthflow complexes (Holocene and Pleistocene?)**—Locally includes block slides of sedimentary rock and extensive earthflow tongues

Qd — **Debris slopes, undifferentiated (Holocene and Pleistocene?)**—Mapped only on flanks of Crested Butte Mountain. Mostly forested talus, talus streams, and protalus ramparts derived from the Crested Butte laccolith. Locally includes landslides, rock falls, and avalanche debris. Talus fields on northeast flank of mountain are furrowed by linear troughs and ridges possibly due to deep-seated gravity slumping in underlying Mancos Shale

morainal deposits

Qm — **Moraine deposits, undifferentiated (Pleistocene)**—Clay- to boulder-size, unsorted till deposits with subangular to rounded clasts of bedrock derived from local and distant sources. Forms hummocky topography and many lateral and recessional moraines. Mostly of Pinedale age. Deposits of pre-Pinedale till are locally present 1,200–1,600 ft (365–490 m) above valley floors

Qu — **Undifferentiated surficial deposits (Holocene and Pleistocene)**—Mostly colluvial slope wash forming soil-covered, vegetated slopes. Locally includes talus and glacial deposits. Many are characterized by solifluction and by mass creep, slumps, small landslides, and earthflows on relatively unstable slopes overlying shaly bedrock

Fig. 2-10. Description of common Quaternary map units mapped on Snodgrass Mountain by Gaskill et al. (1991).

For example, we map Qal (correlative with Gaskill's Qa), Qaf (correlative with Gaskill's Qf), and Qgt/Qpt/Qbt (correlative with Gaskill's Qm).

One of the keys to understanding the local geomorphology is the presence of latest glacial lateral moraines (our map units Qpt [Pinedale till], Qbt [Bull Lake till]) on the eastern margin of the GHU 1-5 landslide complex. During the latest Pleistocene glaciation, ice from the East River glacier spilled through the saddle between Mt. Crested Butte and Snodgrass Mountain. We infer that this west-flowing ice eroded the SE flank of Snodgrass Mountain below an elevation of about 9800 ft, which coincides with the middle of GHUs 1B, 3, and 5, based on the following evidence.

The lower SE side of Snodgrass Mountain is composed of a relatively gentle bench sloping 8° SE (northern half of GHUs 1B and 3, GHU 6) with a steep slope band at its toe. This steep slope band runs NE-SW across the lower face of the mountain between elevations 9750-9900 ft (at its NE end) and 9600-9750 ft (at its SW end). The 150 ft-high slope band averages a 21° slope to the SE, exposes Mancos Shale on its face, and is the site of several springs (Fig. 2-11).

At the base of this slope band lies the young earthflow mapped by USFS (2006; GHU 4). This earthflow has a very anomalous orientation, in that it trends southwest, perpendicular to all the other landslides and to the local fall-line. The earthflow lies in a swale that parallels contours, at about the same elevation as the Qpt lateral moraine east of the East Slide (GHU 5). This swale could be explained as the product of latest glacial meltwater erosion, as the runoff from Snodgrass Mountain encountered the Pinedale ice margin and was forced to flow southwest along it. The earthflow does contain large porphyry boulders on its surface that look like glacial erratics.

All terrain south of the slope band is underlain by a thicker section of Quaternary deposits than exists above the slope band. Drilling shows that there is an additional 30-40 ft of bouldery Quaternary deposits overlying Mancos Shale here. Seismic refraction surveys (Chapter 4) also confirm the presence of a thick low-velocity deposit that is absent above the slope band. Based on this data and the presence of large surface boulders, we infer that the Pinedale glacial limit crossed Snodgrass Mountain between 9930-9870 ft, based on the preserved lateral moraine directly east of the East Slide.

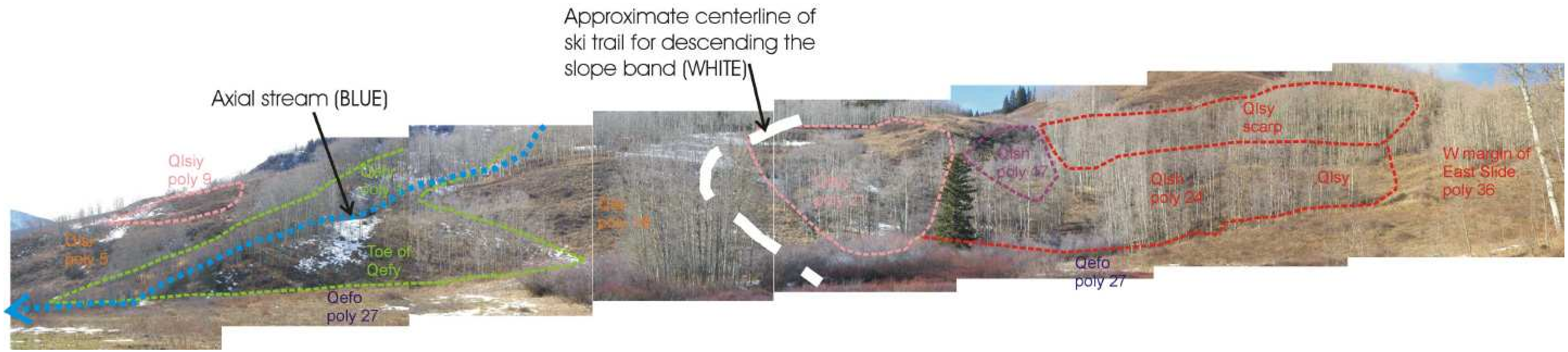


Fig. 2-11. Annotated panoramic photograph of the steep slope band that crosses the middle of the landslide area on the southeastern slope of Snodgrass Mountain. Landslide ages and polygon numbers correspond with those on Plates 1 and 2. Skiers will be brought down the slope band on the most stable part, a ridge nose that lies between the axial stream and Qlsiy (polygon 21). This photo was taken from the approximate site of the upper lift terminal of the Snodgrass/Gold Link connector lift, which will traverse the North Village

2.5 Landslide Deposit Mapping

2.5.1 Design-level landslide mapping

None of the previous landslide mapping was detailed enough to support the present ski area design, so we prepared such a design-level landslide map. This design-level map incorporates all the previous geologic and landslide mapping (Table 2-1), plus limited field reconnaissance performed by the author in Fall 2006 and summer 2007.

Version 2.0 of the design-level landslide map is shown in Plate 1. This map portrays 56 landslide deposit polygons, 23 headscarp erosion areas, and 57 small slump scarps as mapped by RCE (1995). Almost all of the landslide polygons mapped in this study occur in GHUs 1-5.

The total area of all 56 landslide deposit polygons is 230 acres, with an average polygon size of 4 acres. The largest polygon is no. 16 (the Slump Block, at 20.2 acres) and the smallest polygon is 0.04 acres. About half of the polygons are smaller than 1.5 acres.

All polygons are divided into type and age classes. Type classes are slumps (Qls*x*) and earthflows (Qef*x*). Age classes are derived from McCalpin (1984) and include historic (<100 years; Qlsh); young (late Holocene; Qlsy, Qefy); intermediate-young (late to middle Holocene; Qlsiy); Intermediate (middle Holocene; Qlsi); intermediate-old (early Holocene; Qlsio); and old (pre-Holocene; Qlso, Qefo). As in most areas, the largest slides are the oldest, with younger reactivations being progressively smaller. So far, only 3 historic landslides (Qlsh) have been found; on the West Face (GHU 10A, polygon 46), on the Slump Block (GHU 2, polygon 13), and at the base of the Middle Slide Complex (GHU 3, polygon 17). These slides are described more fully in Sec. 2.3.4.

In addition to the landslide deposit polygons, we map 23 headscarp erosion areas upslope of landslide deposits. These headscarps are generally underlain by the local bedrock (either Tp or Km), but in some cases the headscarp occurs within a landslide mass and is thus underlain by older landslide deposits.

Finally, we include the 57 small slump scarp line symbols mapped by RCE (1995). These slump scarps were classified by RCE as prominent (red lines on Plate 1) or old (blue lines on Plate 1). We infer that the prominent scarps are late Holocene and thus generally correlate with the young (Qlsy) or young-intermediate (Qlsiy) age class of landslide deposits, while the old scarps are probably middle Holocene and correlate with the intermediate age class (Qlsi) of landslide deposits. Thus, where prominent scarps exist within a Qlsiy or older landslide deposit polygon, they represent small, local reactivations that are younger than the bulk of the landslide deposit.

The landslides on the southeastern slope of Snodgrass Mountain are morphologically classified as either slumps or earthflows (Cruden and Varnes, 1996). We did not map any debris-flow deposits (Table 2-3). The historic slumps have moved up to 35 ft (polygon 46, GHU 10A, West Face) or 4-5 ft (polygon 23, GHU 2, Slump Block) since fences were built, perhaps in a single movement, perhaps in multiple discrete movements, or as slow, continuous soil creep. The distinction between landslide creep and surficial soil creep is discussed in Chapter 3.

2.5.2 Comparison of USGS geologic mapping of Gothic quadrangle (Gaskill et al., 1991) with GHUs defined by USFS (2006).

The USGS geologic map of the Gothic quadrangle (Gaskill et al., 1991) mapped GHUs 1A (all but NE corner), 1B, 2, 3 (south half), 4, 5A, and 5B as landslide complexes (Fig. 2-5). This indicates that USGS thought 100% of the terrain there was composed of landslide deposits, so in this respect the USGS map agrees with the USFS (2006) report, that these GHUs on the southeastern slope of the Mountain comprise the most consistently unstable terrain in the project.

In contrast, Gaskill et al. mapped GHUs 1 (NE corner), 3 (north half), 6, 7, 8, 9, 10A, 10B, 11, 12, and 13 as being composed of Tertiary porphyry and "undifferentiated Quaternary deposits" (map unit Qu on Figs. 2-4, 2-5). These undifferentiated deposits can, in places, contain *"solifluction and mass creep, slumps, small landslides, and earthflows on relatively unstable slopes overlying shaly bedrock."* For example, small slump scarps are shown on their map as line symbols in GHUs 6 (Chicken Bone), 11, and 12. This comparison indicates that these GHUs are composed partly of landslide deposits, partly of non-landslide Quaternary deposits such as talus and colluvium, and partly of stable bedrock.

Finally, GHUs 7, 8, and 9 do not even contain any slump scarps, as portrayed by Gaskill et al. (1991) and RCE (1995). This implies that those GHUs are composed of non-landslide Quaternary deposits such as talus and colluvium, and partly of stable bedrock, with few to no recognizable landslides.

2.5.3 Comparison of design-level mapping with GHUs of USFS (2006)

The goal of design-level landslide mapping was to subdivide the GHU polygons of USFS (2006) into areas of landslide deposits, landslide source areas, non-landslide Quaternary deposits, and stable bedrock. Plates 1 and 2 show the distribution of landslide deposits, landslide source areas, non-landslide Quaternary deposits, and stable bedrock in each of the GHUs. The distribution of landslide types and ages (without regard to area) in each GHU is shown in Table 2-3.

Table 2-3. Comparison of landslide ages assigned to GHUs in USFS report (2006), with age classes of more detailed landslide polygon mapping from this study. Total landslide polygons=56; total scarps=80.

GHU, from USFS, 2006	"AGE", from USFS, 2006[1]	Number of Landslide Polygons Mapped in This Study, by Age Class											
		Undivided		historic	young			Interm-young	Intermediate		Interm-old	Old	
		Qls	Qef	Qlsh	Qlsy	Qefy	Prom scarps	Qlsiy	Qlsi	Vague scarps	Qlsio	Qlso	Qefo
1A	h-y						11	2	2	3			
1B	h					1	4	3	2	1	1		
2	h	1		1				1	1	2		1	
3	h-y			1	3		6	1	5	2			
4	h-y												1
5A	h-y						3	1	3				
5B	h	1			3			2					
6	h-y				3			2	1				
7	h-y				1		2						
8	h-y	**No landslides mapped**											
9	m-o	**No landslides mapped**											
10A	y-m	**No landslides mapped**											
10B	h-y			1	1		1						
11[2]	h-m						13			2			
12	h-y						1	1	1	6		1	
13	h-o	**No landslides mapped**											
14[3]	N/A		7										

[1] Qls= soil slump; Qef= earthflow. Suffixes: h, historic (active); y, young; m, mature (intermediate); o, old. After McCalpin, 1984.
[2] not mapped in this study; no development actions proposed in this GHU.
[3] an additional GHU added in this study, east and southeast of GHU 5; no development actions proposed there.

2.5.3a GHUs 1A and 1B (Fig. 2-7)

GHUs 1A (West Facet) and 1B (West Slide) comprise the westernmost part of the GHU 1-5 landslide complex at the base of Snodgrass Mountain (Fig. 2-12). The West Facet is a steep, triangular slope with its apex at 10,775 ft elevation. The upper half of the West Facet is a crescent-shaped erosional headscarp area in which there are little to no landslide deposits, and the ground surface exposes residuum of Tertiary porphyry. The northern half of this crescent was mapped by Gaskill et al. (1991) as underlain by Tertiary porphyry, whereas the southern half was mapped as half Tertiary porphyry and half non-landslide Quaternary deposits (undivided) such as colluvium. We did not map any landslide deposits in this crescent.

The central and lower part of the West Facet is composed of 6 landslide deposit polygons, most of which are assigned intermediate (Qlsi) or intermediate-young (Qlsiy) ages (Fig. 2-12, Table 2-3). The older set of landslide deposits (Qlsi) underlies slightly higher topography, and has the appearance of erosional ridges, into which the younger landslides are inset (Qlsiy).

RCE (1995) mapped 11 prominent scarps and 3 older scarps on the West Facet. We use 9 of these 11 prominent scarps and 2 of the 3 older scarps to define the upslope limit of our younger landslide deposits (Qlsiy).

GHU 1B lies downslope of GHU 1A, with the boundary line trending from NE (elevation 10,070 ft) to SW (elevation 9920 ft). All but one of our landslide polygons mapped in GHU 1A continue into GHU 1B, and there are 4 additional “new” landslide polygons in 1B. The central part of 1B is marked by the oldest landslide deposit (Qlsio) which occupies the highest topography. This ridge is the downslope continuation of the two Qlsi ridges mapped in GHU 1A, but due to the increasing incision of streams in 1B, it stands even higher above adjacent terrain. Due to this increase in height, we assign it an older age. South and east of the Qlsio ridge, younger landslides (Qlsiy, Qlsi) are inset into the edges of the ridge with headscarps.

We drilled 2 boreholes into GHU 1B. PZ-8 at its head encountered weathered Mancos Shale at a depth of 46 ft, whereas at PZ-9 in the center the same contact was 80 ft below surface. Static water level was 19-26 ft below surface in July 2007.

The northern part of GHU 1B is composed of landslide polygon 1, a long, young earthflow (Qefi through Qefy). This earthflow is bounded on the east by the axial, perennial stream draining the SE slope of Snodgrass Mountain. The western boundary of the earthflow is another shallower spring-fed stream. Polygon 1 can be divided into 3 parts based on surface morphology. The upper 1/3 has a very smooth surface appearance very similar to Qlsi surfaces nearby. There are no indications of shallow groundwater or of young movement in this part of the earthflow, so we classify it as Qefi. The middle 1/3 of earthflow has some subdued hummocky topography and a few springs at the head; we classify it as Qefiy. The lower 1/3 of the earthflow has well-developed scarp-and-bench topography, and it is this lower 1/3 that has flowed down the steep slope band

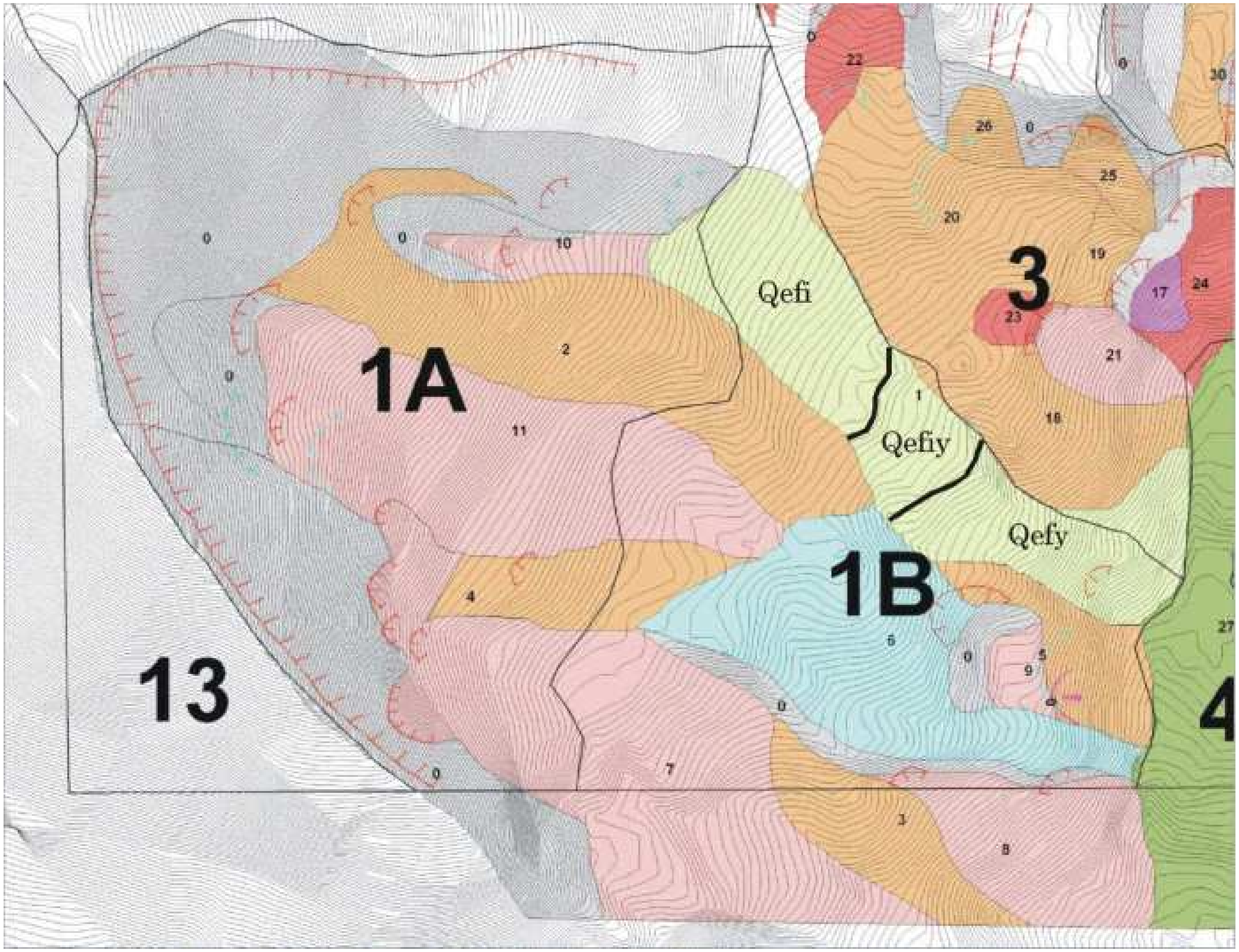


Fig. 2-12. Design-level landslide map of GHUs 1A and 1B. Landslide deposit polygons are numbered, as on Plate 1. Zeros indicate erosional scarp areas. Polygon color indicates deposit type and age; purple, Qlsh; red, Qlsy; pink, Qlsiy; orange, Qlsi; light blue, Qlsio; yellow, Qefy; green, Qefo. Subdivisions of Polygon 1 are shown by thick black lines. Red line with hachures, prominent scarps of RCE (1995); blue lines with hachures, old scarps of RCE (1995). Large black numbers and black lines show GHU polygons defined by USFS (2006). Thin rectangular line at left and bottom is CBMR permit boundary. Contour interval is 5 feet.

and 150 ft out onto the Lower Earthflow below. Due to the presence of two flanking streams in this part, the entire earthflow has a wet appearance and we infer that groundwater is shallow throughout the area. The young age (Qefy) is assigned due to the prevalence of young-looking, transverse scarp-and-bench topography. We did not observe any fresh, unvegetated or open cracks in this polygon, and no fences cross it, which would prove historic movement, so we classify the earthflow as young (late Holocene). The minimum average movement rate of the Qefy toe since glacier retreat is 150 ft/15,000 years, or 0.01 ft/yr (ca. 0.1 inch/yr).

PZ-6 is located in the upper (Qefi) part of the earthflow, and reached Mancos Shale bedrock at depth of 81 ft. There were two zones of saturation, an unconfined upper zone from 21-32 ft, and a confined lower one from 60-81 ft. These values are very similar to those at PZ-5, which is just east of the earthflow, where bedrock was encountered at 85 ft and the two zones of saturation were at 21-30 ft and 64-80 ft.

2.5.3b GHUs 2 through 5 (Fig. 2-13)

GHUs 2 through 5 comprise the eastern part of the GHU 1-5 landslide complex at the base of Snodgrass Mountain (Fig. 2-13), as follows:

GHU 2, the "Slump Block" of Baum (1996)
GHU 3, the Middle Slide Complex
GHU 4, the Lower Earthflow
GHU 5A, upper part of the East Slide Complex of all previous workers
GHU 5B, lower part of the East Slide Complex of all previous workers

The "Slump Block" of Baum (1996): The Slump Block (GHU 2) is mapped herein as 5 separate landslide polygons (polygons 12-16). Polygon 12 lies at the base of the hill, outside the permit area, and is covered with glacial erratics. It is assumed to be the oldest landslide deposit here, probably pre-Pinedale in age. Piezometer PZ-15 was drilled into this polygon in Nov. 2006, and shows that the till plus landslide deposits are 31 feet thick, overlying Mancos Shale; depth to static water was 33 ft.

Polygon 13 is a small (0.9 acres) historic landslide that has detached from the southern slope of polygon 16, which makes up the bulk of the Slump Block. This slump has pushed the Allen Ranch boundary fence about 4 feet out of line, so clearly has experienced historic movement (Fig. 2-14).

Polygons 14 and 15 are larger and older versions of polygon 13, comprising reactivations of the south flank of the slump block. Both are characterized by linear ridges and intervening swales, several meters high, that trend NE-SW. Based on the presence of large porphyry boulders, at least some of these ridge are lateral moraines of the latest (Pinedale) glaciation. Other south-facing scarps appear to be additional landslide headscarps

The bulk of the Slump Block is composed of polygon 16 (20.2 acres). This polygon lacks the ridges and swales of the other polygons, and is typified by a smoother topography. Thus it is assigned an old age (Qlso). PZ-14 lies in the center of this polygon and was 117 ft deep, the deepest borehole on the mountain. The borehole never reached the top of Mancos Shale bedrock. Instead, 4 Quaternary deposits are interpreted here: young (Pinedale) till (0-33 ft), Pinedale outwash (33-47 ft), old landslide deposits? (47-90 ft), and very old till (90-117 ft). According to the seismic

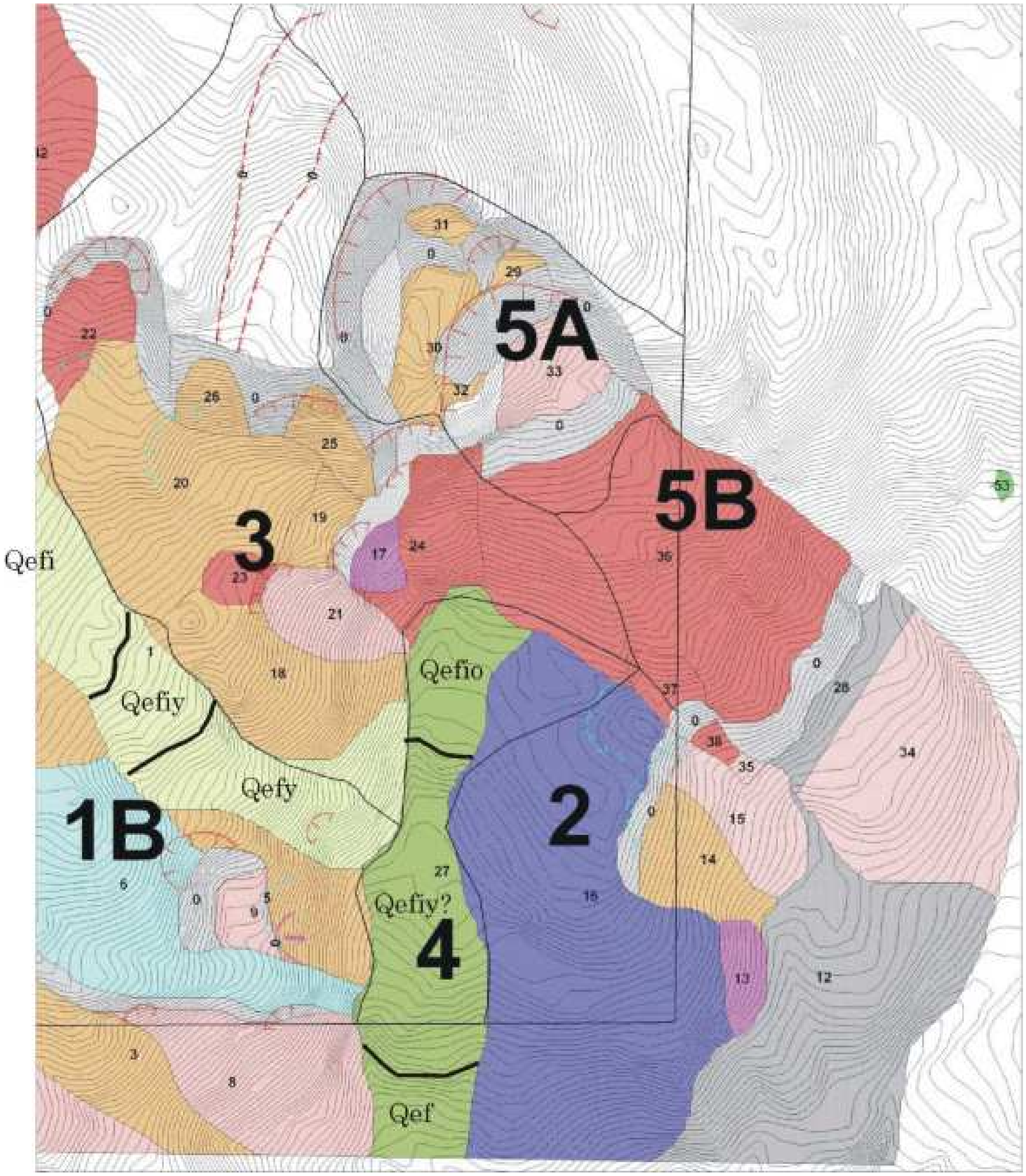


Fig. 2-13. Design-level landslide map of GHUs 2 through 5. Landslide deposit polygons are numbered, as on Plate 1. Zeros indicate erosional scarp areas. Polygon color indicates deposit type and age; purple, Qlsh; red, Qlsy; pink, Qlsiy; orange, Qlsi; light blue, Qlsio; dark blue, Qlso; yellow, Qefy; olive green, Qefo; gray, Qls; bright green, Qef. Polygon 27 (Lower Earthflow) has been subdivided into 3 parts which do not follow the color scheme. Red line with hachures, prominent scarps of RCE (1995); blue lines with hachures, old scarps of RCE (1995). Large black numbers and black lines show GHU polygons defined by USFS (2006). Thin rectangular line at right and bottom is CBMR permit boundary. Contour interval is 5 feet.

Fig. 2-14. Deformed east-west fenceline crossing the southern part of landslide polygon 13 (GHU 2, Qlsh). The leaning fenceposts coincide with a southward bulge in the fenceline of about 4 ft. An older set of wooden fenceposts lies flush with the ground, indicating that the tilted fenceposts in this photo are a replacement set of fenceposts, which have been subsequently deformed. Where the fence crosses the crest of the polygon 13 headscarp, there are 2 sets of repair wire installed to accommodate the southward extension of the fence, suggesting 2 different episodes of fence deformation and subsequent repair. Thus, the 4 ft of misalignment of the current fence represents only the latest deformation episode.

refraction surveys (Chapter 3), Quaternary deposits in GHU 2 are uniformly 100-140 ft thick, or about 2-4 times as thick as above the steep slope band. This interpreted stratigraphy seems to confirm that the Slump Block, if it is a landslide block at all, predates the Pinedale glaciation. Depth to static water was 31 ft in July of 2007.

The Middle Slide Complex: We divided the Middle Slide Complex into 10 landslide deposit polygons, 2 landslide scarp areas, and 2 bedrock outcrop areas (Fig. 2-13). The landslide polygons are numbered 17 through 26, and range in age from:

-- historic (Qlsh, polygon 17; 0.6 acres)
-- young (Qlsy, polygons 22-24; 4.8 acres)

-- intermediate-young (Qlsiy, polygon 21, 1.9 acres)
-- intermediate (Qlsi, polygons 18-20, 13.9 acres)

Thus, about 75% of the landslide deposits by area are intermediate or intermediate-young.

The northern 1/3 of the complex is mapped as porphyry bedrock by Gaskill et al. (1991), and we did not observe any landslide deposits there. Separating the bedrock terrain from the landslide terrain is a thin band of erosional headscarp areas totaling 3.0 acres.

Trending NE-SW across the lower part of GHU 3 is a band of oversteepened slopes. This “steep slope band” runs NE-SW across the GHU between elevations 9750-9900 ft (at its NE end) and 9600-9750 ft (at its SW end). The 150 ft-high slope band averages a 21° slope to the SE, exposes Mancos Shale on its face (Fig. 2-11) and is the site of several landslides and springs.

Two boreholes were drilled into the Middle Slide Complex. PZ-5 lies in polygon 20 (Qlsi) in the western part of the complex. Here Mancos Shale bedrock was encountered at 85 ft below the surface and the two zones of saturation were at depths of 21-30 ft and 64-80 ft. PZ-11 lies in polygon 24 (Qlsy) in the eastern part of the complex, but below the steep slope band and just east of Qlsh polygon 17. Depth to Mancos Shale bedrock there is 42 ft and static water level is 52 ft.

Ken’s Crux Slump: The head of GHU 3 is marked by a small rock (?) slump (polygon 22, Qlsy) directly east of Ken’s Crux. The headscarp of this slump exposes an outcrop of resistant in-situ Tp, particularly at its western end. The sill that makes this outcrop forms a relatively narrow ridge north of polygon 22 and south of polygon 42 is this ridge of resistant rock that forms the topographic constriction of Ken’s Crux. Our interpretation thus differs from that of USFS (2006), who assumed that this protruding ridge was underlain by landslide deposits. In our interpretation, based on the constriction and the outcrop, this ridge is a thin septum of unfailed porphyry sill lying between two slump areas that have failed. According to borehole PZ-4, landslide deposits in the center of polygon 22 are 41 ft thick atop Mancos Shale, and the static water level is at 38 ft, perched on the bedrock contact.

The Lower Earthflow: We originally mapped the Lower Earthflow as a single landslide deposit polygon, similar to USFS (2006), and called it an old earthflow (Qefo). The upper 1/4 of this earthflow has a very smooth topography and lacks the scarp-and-bench topography exhibited by the younger earthflow in GHU 1B, described previously. However, in summer of 2007 we recognized 2 internal scarps within this earthflow. The upper scarp separates the very smooth topography above from more hummocky topography below, suggesting that the scarp represents a reactivation of the middle of the Lower Earthflow. The head of this inferred reactivated area lies where the toe of the Upper Earthflow (polygon 1, Qefy) has protruded about 300 ft onto the Lower Earthflow. It is possible that this protrusion surcharged the middle of the Lower Earthflow and reactivated it; if so, the reactivation is younger than Qefy. We classify the middle of the Lower Earthflow as Qefiy?, because it has more subdued topography than Qefy, and thus its exact age is uncertain.

South of the project area the Lower Earthflow is interrupted by another internal scarp. However, we did not field check this area, so we do not know if this scarp represents the toe of the Qefiy reactivated zone, or another internal headscarp. Slide age south of this scarp is only classified as Qef.

According to the drilling (PZ-12 at the head, PZ-13 nearer the toe) and geophysics (West Line, Central Line), depth to Mancos Shale bedrock beneath the Lower Earthflow is 68 ft at PZ-12 and 80 ft at PZ-13.

Upper part of the East Slide Complex (GHU 5A): We map the Upper East Slide as 5 deposit polygons (29-33), all separate slump blocks in the headscarp complex, which comprise about half the GHU (Fig. 2-16). The other half of the GHU is headscarp erosional areas. As a whole, these slump blocks look older than the landslide surface of the Lower East Slide. Borehole SG-3, drilled by Resource Engineering in 1994, lies in the middle of this area (polygon 30); it hit refusal (top of Mancos Shale?) at a depth of 61 ft, with static water level at 42 ft.

Fig. 2-16. Photo of the slump blocks of the upper east Slide, comprising GHU 5A. Most of the view is composed of polygon 30. View to the NE; mountains in distance are on the eastern side of the East River.

Middle and Lower part of the East Slide Complex (GHU 5B): We map the Lower East Slide as 6 deposit polygons (28, and 34-38), all separate lobes of the deposit (Fig. 2-17). Only the uppermost lobes (polygons 36, 37) lie in the National Forest. Polygon 36 comprises about half of the area. As a whole, polygon 36 looks younger than the Upper East Slide, perhaps because of the prominent longitudinal, boulder-covered ridges. These boulders are presumably the slid remnants of the Pinedale lateral moraine that exists just east of the East Slide, and has boulders of similar size and Lithology.

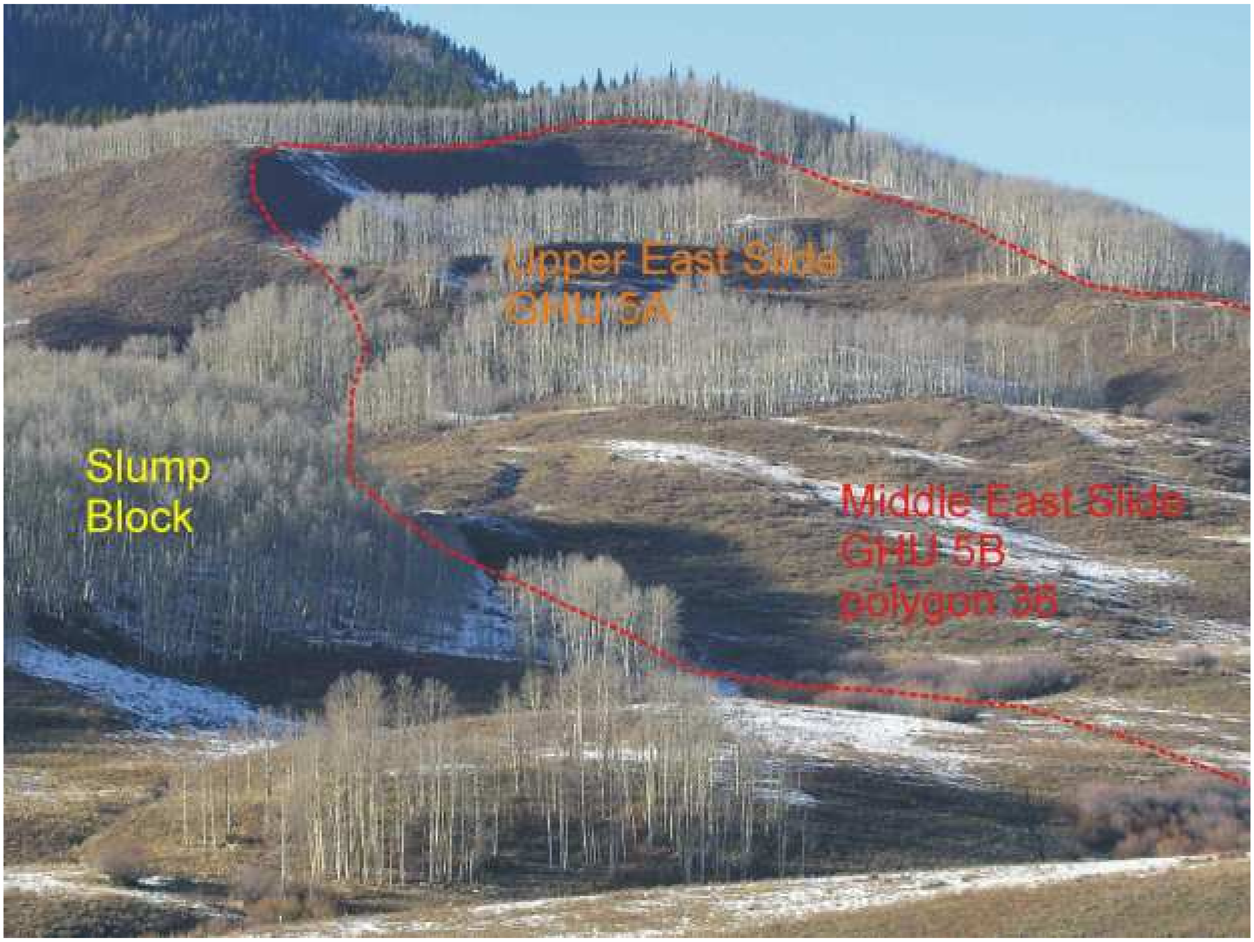


Fig. 2-17. Telephoto view of the upper and middle East Slide, taken from Gothic Road. Slump Block is at left. The East Slide is designated as a “No Disturbance Zone” in the Snodgrass Lite design.

We have more subsurface data on this area than anywhere else on the mountain, with 3 boreholes (SG-4 at the head of polygon 36, PZ-16 in the center of that polygon, and SG-5 in polygon 34 at the toe), plus seismic refraction lines that run the entire length of the East Slide (including GHU 5A). In SG-4 no porphyry fragments were encountered below a depth of 55-60 ft and blow counts increase there, so we interpret that as the top of weathered Mancos Shale. A second increase of blow counts at 70 ft probably indicates the top of intact shale. Depth to static water was only 11.5 ft in

October of 1994, probably reflecting artesian conditions. In PZ-16 in the center of polygon 36, bedrock was encountered 38 ft below surface with a saturated zone from 27-31 ft. At the toe of the East Slide, the top of weathered shale was encountered 70 ft below surface, with the top of intact shale at about 80 ft. The interval between 55-65 ft contained charred and other organic material, plus an anomalous mixture of porphyry cobbles and shale. This probably represents the basal shear zone and an overridden ground surface. Static water was 31 ft below surface in Oct. of 1994.

2.5.3c GHUs 6 through 8 (Fig. 2-18)

GHUs 6-8 are almost entirely underlain by in-situ bedrock, and have few recognizable landslide deposits. This interpretation follows that of previous mappers (i.e., Gaskill et al., 1991; Irish, 1996; Baum, 1996), who did not interpret GHUs 6-8 as containing any landslide deposits. About 80% of the GHU is composed of scarp-and-bench topography that trends NW-SE, which is the perpendicular to the trend expected for landslide-related topography, which would parallel contours. Unlike USFS (2006), who interpreted this topography as indicating landsliding, we agree with the three mappers above who interpreted this area as bedrock. The scarps and benches are inferred to represent thin resistant sills of porphyry and thin nonresistant interbeds of Mancos Shale, in the transition zone. Borehole PZ-1 lies at the head of GHU 6 and encountered weathered shale at 51 ft below surface, with a saturated zone from 22.5-46 ft. The upper 51 ft represent Quaternary colluvial deposits (silty clay and cobbles, some gravel, scattered boulders) derived from the East Facet.

We map 6 landslide deposit polygons in GHU 6 (Chicken Bone; polygons 39-44), but those deposits compose less than 20% of the area of the GHU. Each deposit is associated with a spring area. Borehole PZ-2 lies at the head of polygon 39 and encountered weathered shale at only 16.75 ft below surface, with a saturated zone from 10.5-16.75 ft. The upper 16.75 ft represent Quaternary landslide deposits (clayey silt and cobbles).

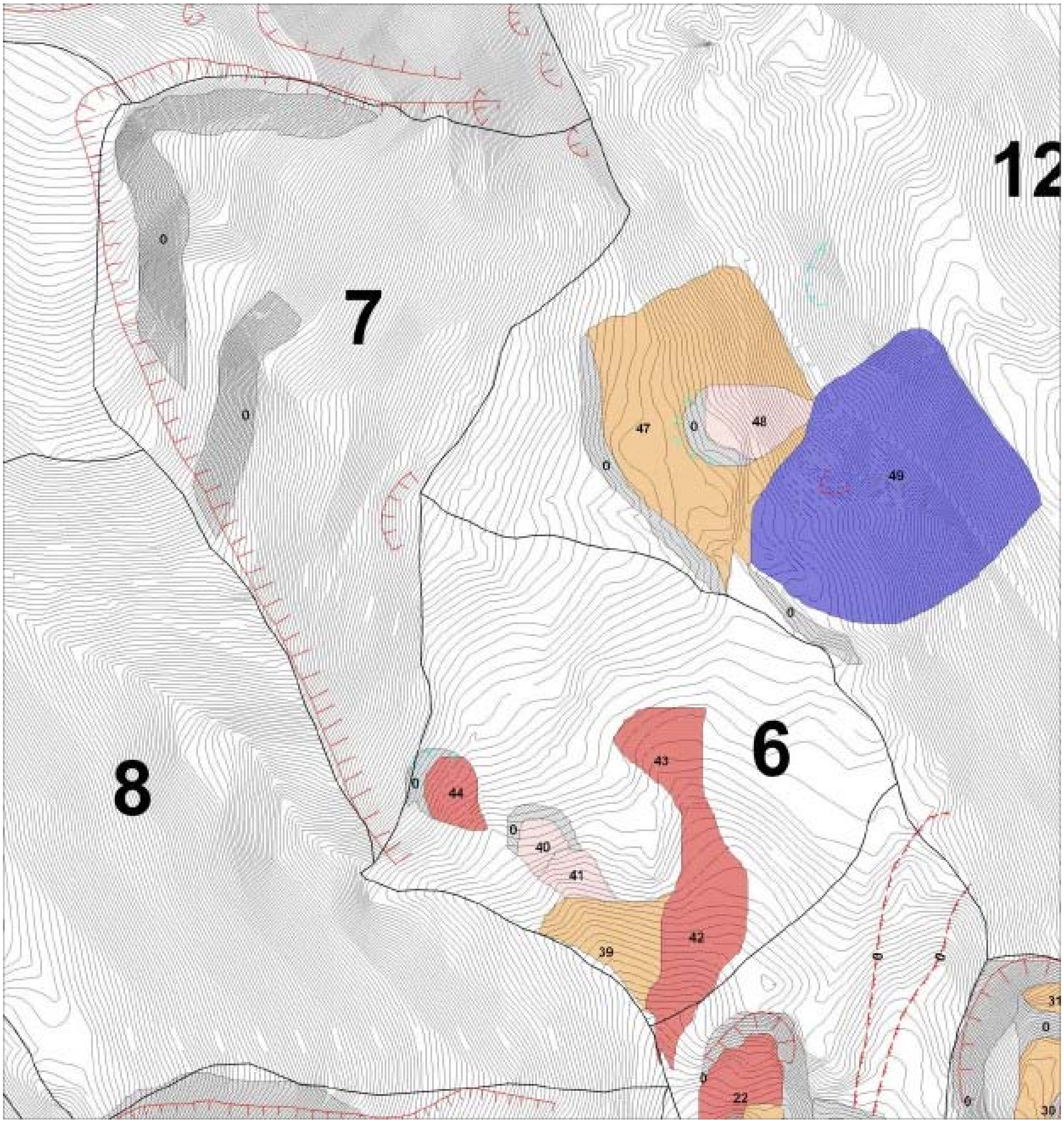


Fig. 2-18. Design-level landslide map of GHUs 6 through 8. Landslide deposit polygons are numbered, as on Plate 1. Zeros indicate erosional scarp areas. Polygon color indicates deposit type and age; red, Qlsy; pink, Qlsiy; orange, Qlsi; dark blue, Qlso. Red line with hachures, prominent scarps of RCE (1995); blue lines with hachures, old scarps of RCE (1995). Dashed red lines, inferred pull-away troughs. Large black numbers and black lines show GHU polygons defined by USFS (2006). Contour interval is 5 feet.

GHU 7 (the East Facet) is heavily forested and so interpretation is based on airphoto interpretation and the 5-ft contours. Neither Gaskill et al. (1991), Irish (1996), or

Baum (1996) thought there were landslide deposits there, and we cannot observe any on the aerial photographs. RCE (1995) did include the East Facet within their East Slide, but only mapped a single individual scarp there, in contrast to their treatment of the West Facet, where they mapped 14 scarps. However, the 5-ft contours do show benchy terrain on the East Facet, probably the result of differential erosion of porphyry sills and Mancos Shale I the transition zone. Figs. 2-5 and 2-18 show these steep areas as questionable headscarps, without any identifiable landslide deposits downslope. Therefore, we do not think there are significant landslide deposits in the unconsolidated deposits that mantle the lower part of the East Facet. Those deposits are exposed in long roadcuts along the Snodgrass Road, where they appear to be colluvium (Fig. 2-19).

Fig. 2-19x. Roadcut exposures of the colluvium at the base of the East Facet. Clasts are all Tertiary porphyry and most of matrix is grussy. Note field vehicle for scale at right.

GHU 8 is a thickly forested slope on the western side of the axial drainage, opposite GHUs 6 and 7. We made a field reconnaissance of this slope in early October, 2006, and did not observe any landslide deposits on the ground surface. This fact was reported to GMUG at our meeting in Delta on October 4, 2006.

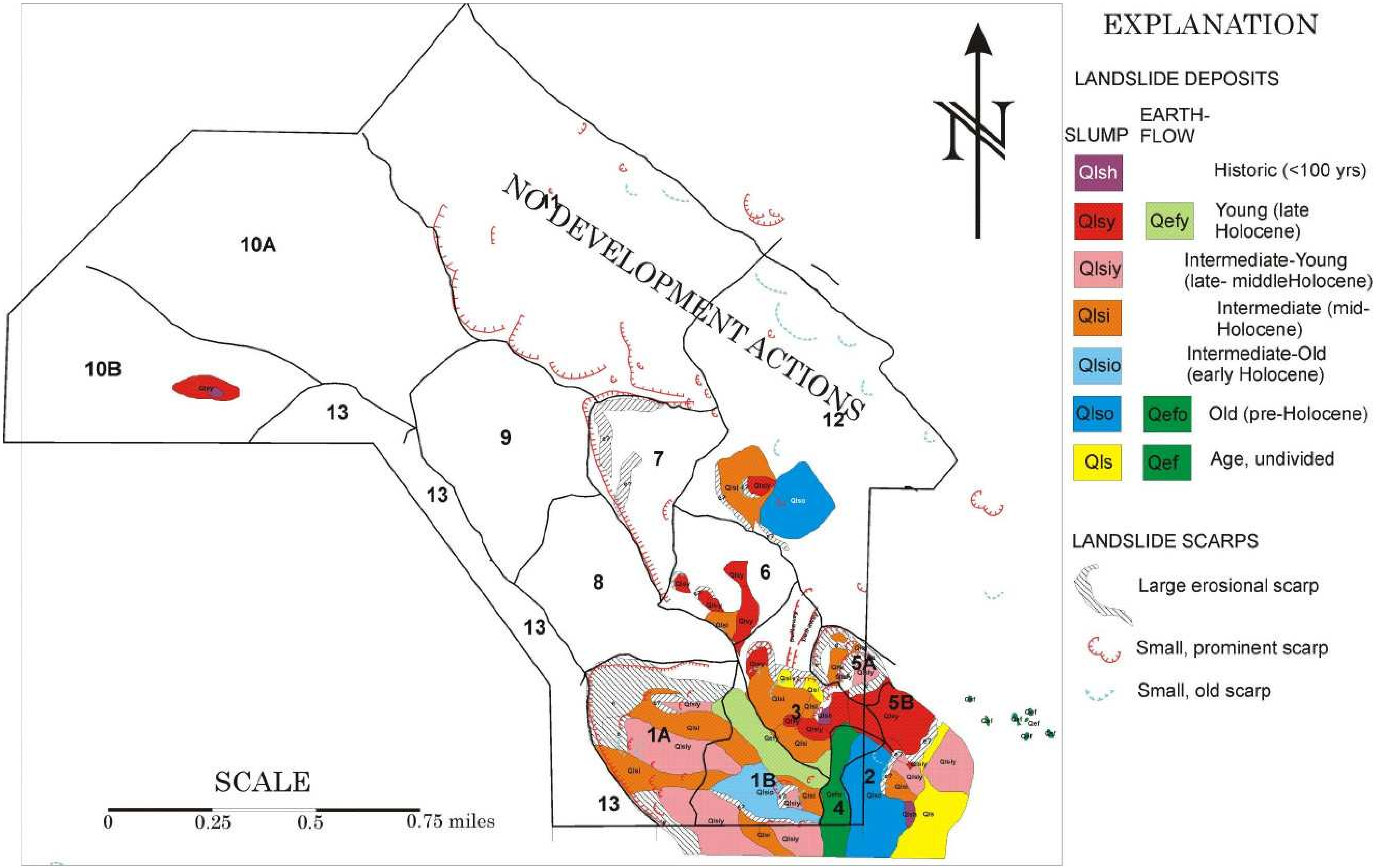


Fig. 2-19. Simplified design level landslide map of the Snodgrass permit area.

2.5.4 Landslides outside of the Southeastern Slope

There are several landslides mapped on the three other slopes of Snodgrass Mountain, aside from those on the SE slope (Fig. 2-19). For example, the northeast face of Snodgrass Mountain, which slopes down to Gothic Road and the East River, exhibits arcuate scarps all along its crest. That NE face is outside of the CBMT permit boundary and no disturbance will occur there. Accordingly, we did not map this slope by either photo-interpretation or field checking. Although RCE (1995) mapped several scarps on that slope.

The SW face of Snodgrass Mountain slopes steeply down to Washington Gulch (Fig. 2-20). The contact between Mancos Shale and the overlying Tertiary laccolith is mapped about halfway up this face by Gaskill et al. (1991) as a simple contact, with laccolith porphyry extending from the contact up to the summit, and Km from the contact down to the valley floor. However, field checking reveals that the lower face is actually underlain by a transition zone of alternating Km and thin Tp sills, just as was found on the southeastern side of Snodgrass (Fig. 2-21). This transition zone extends from the bottom of the laccolith (located at the head of Qlsy on Fig. 2-20) all the way to the base of the slope where it becomes covered by till (Fig. 2-21b).

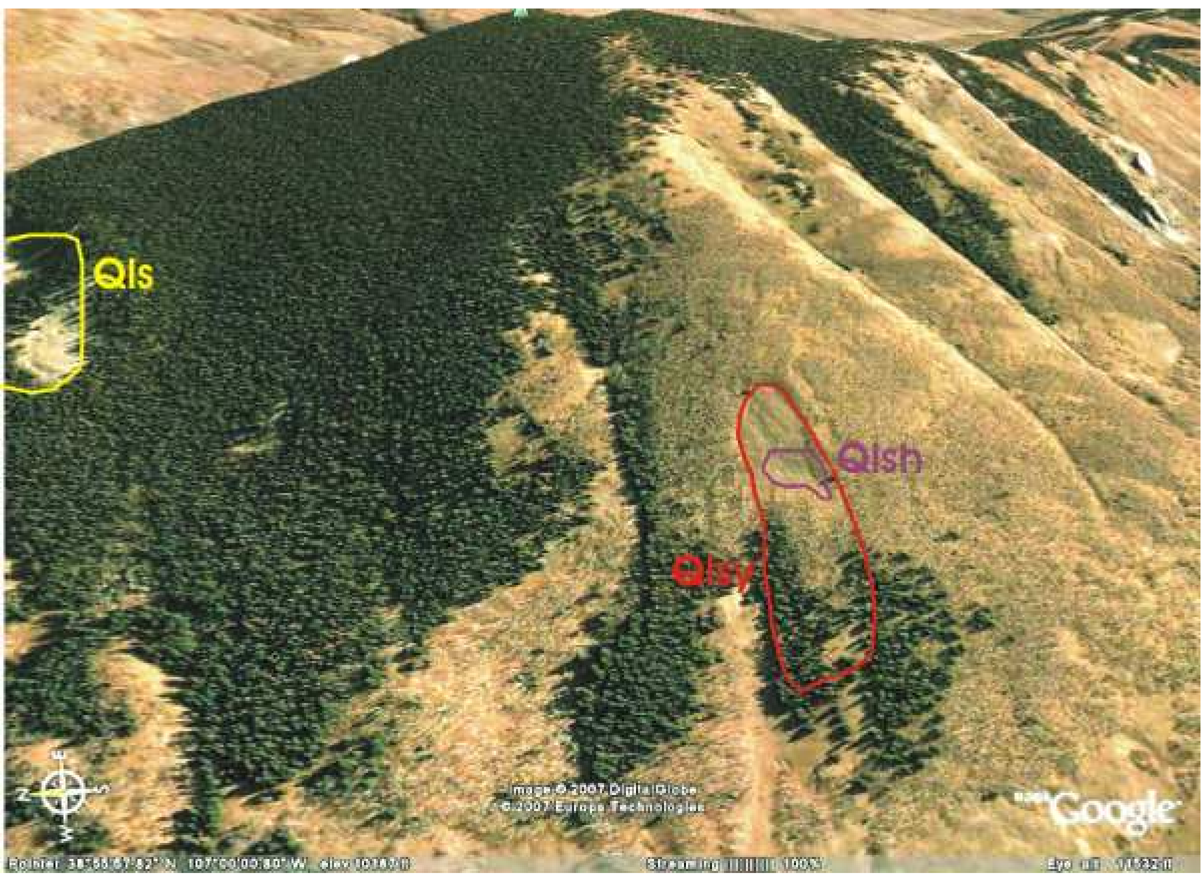


Fig. 2-20. Google Earth image of the southwest face (at center) and Northwest face (at left) of Snodgrass Mountain (summit at top center). View looking east.

Fig. 2-21a. Thin Tp sill intruded into Km about midway up the SW face of Snodgrass Mountain. View to SE. Note that bed has an apparent NW dip (toward the camera).

Fig. 2-21b. Thin Tp sill intruded into Km at base of the SW face of Snodgrass Mountain. View to NW toward the floor of Washington Gulch. The sill forms a steepened slope segment extending from center to upper left center. Note that bed has an apparent NW dip (away from the camera).

Overall this slope is much steeper than any of the slopes on the southeastern side of Snodgrass. Segments of the face underlain by Km generally slope at 25-30 degrees, whereas segments underlain by Tp slope from 30-35 degrees. Due to the granular, well-drained nature of the residuum derived from Tp, the slopes underlain by porphyry do not show signs of either landsliding or accelerated creep (see annotated photographs in APPENDIX D2.4 on DVD-ROM). The situation is quite different in the transition zone, however. Many slopes in the transition zone show anomalous tree shapes suggestive of accelerated creep (Fig. 2-22). This is especially true near the top of the transition zone, where slopes are generally steeper than 25 degrees. We infer that creep is occurring in shallow weathered Km overlain by a thin veneer of grussy, porphyry-derived colluvium.

Fig. 2-22. Anomalous tree shapes in an aspen grove at 10,550 ft elevation on the SW face of Snodgrass, on the north side of the S-most gully in the permit area. This is near the top of the transition zone.

The only mappable landslides on the SW face occur in the transition zone (Fig. 2-20). The head of Qlsy polygon 45 is at the bottom of the laccolith, and the entire upper half of the slide exposes only Km at the surface. Likewise, Qlsh polygon 46 represents a reactivation in Km, which has deformed the E-W USFS boundary fence about 35 feet. Qlsy narrows about halfway down its extent, due to its intersection with a thin (5 m?) sill of Tp.

The only other landslide in this area is the one mapped on the NW face of Snodgrass Mountain by Gaskill et al (1991). This failure also appears to have detached just below the top of the transition zone, because a thin band of in-situ Km is mapped just at the top of the headscarp. We did not field check this landslide, so have no age classification for it. The proximate cause of the slide is inferred to be erosional oversteepening of the base of the NW face, from the spillover ice lobe that flowed through the saddle between Snodgrass and Gothic Mountains. Thus, the initiation of the landslide is probably slightly post-Pinedale.

2.5.4 Landslide Drilling

We drilled 14 new boreholes in 2006-2007 (Fig. 2-23), to supplement the 5 boreholes drilled by Resource Engineering in 1994. All boreholes were drilled through the Quaternary (unconsolidated) deposits and as far into the Mancos Shale as possible, before refusal. However, one hole (PZ-14) did not reach shale bedrock after 117 ft, the limit of our auger rig. Where multiple saturated zones were encountered, the initial borehole was used for a deep piezometer, and a 2nd borehole was drilled for a shallow piezometer in the perched layer. In the sections below we summarize the geology and hydrology of the borehole logs.

2.5.4.1 Drilling Above the Steep Slope Band (boreholes PZ-1, -2, -4, -5, -6, -8, -9)

Of the 7 boreholes above the steep slope band (Fig. 2-23), most encountered the top of Mancos Shale bedrock between 41 and 60 ft below surface. PZ-2 hit this contact at an anomalously shallow depth of 16.75 ft, where the rig hit refusal on shale. In PZs 5 and 6 the top of shale is considerably deeper, from 81-85 ft below surface. These deeper values suggest that there was a preexisting valley eroded and then backfilled with earthflow deposits near the present axial stream.

The deposits above bedrock are poorly sorted mixtures of porphyry clasts (up to boulder size) in a matrix of weathered gray shale. Based on our 2 backhoe trenches (discussed later), we interpret these deposits as landslide deposits.

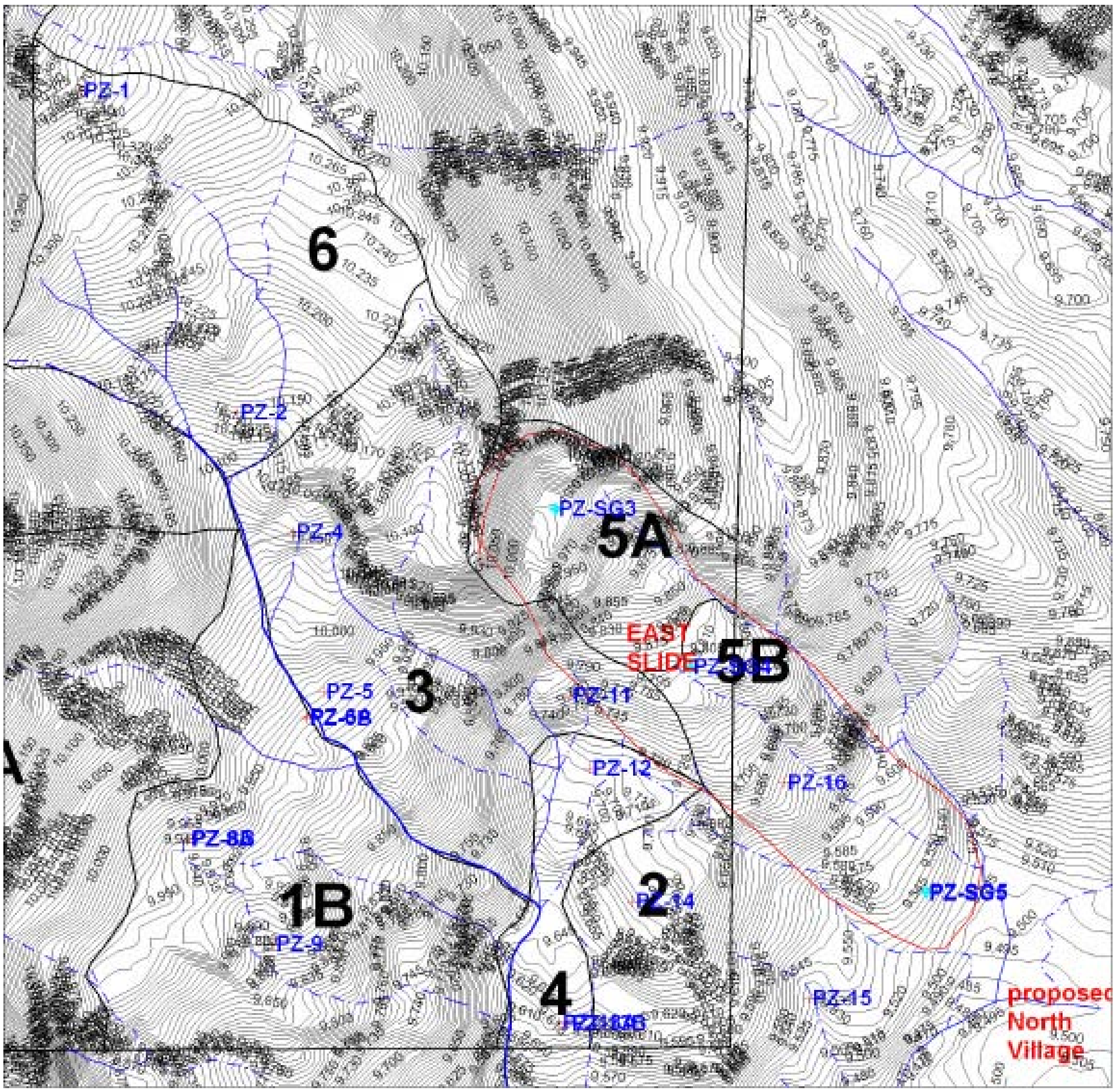
In all the boreholes except PZ-8, there is a zone of saturation atop the Mancos Shale in the basal landslide deposits. This zone ranges from 3-23 ft thick. However, in the deeper holes PZ-5 and -6, there is a higher perched zone of saturation from 21-32 ft below surface. Where there are two zones of saturation, piezometric heads are higher in the lower zone (see Chapter 6).

Table 2-4. Depth data from PZs 1-9.

GHU	Borehole number	Total Depth (ft below surface)	Depth to Shale (ft below surface)	Upper saturated zone (ft below surface	Lower saturated zone (ft below surface
6	PZ-1	67	51	22.5-46	
6	PZ-2	20	16.75	10.5-16.75	
3	PZ-4	44	41	38-41	
3	PZ-5	89	85	21-30	64-80

1B	PZ-6	86	81	21-32	60-81
1B	PZ-8	60	46	19-30.25	41-46
1B	PZ-9	81	60	26-46	
	Mean[1]		54.4		
	Mean[2]		43		

[1] all boreholes
[2] excluding PZ-5 and -6



Fig, 2-23. Map of the piezometers installed in the landslide complex, SE slope of Snodgrass Mountain. Overprinted labels indicate a shallow and deep piezometer pair. Contour interval is 5 ft; large bold numbers show GHUs.

2.2.4.2 Drilling Below the Steep Slope band (boreholes PZ--11, -12, -13, -14; SG-3, -4, -5)

Of the 7 boreholes below the steep slope band (Fig. 2-23), most encountered the top of Mancos Shale bedrock between 31 and 60 ft below surface, although PZ-14 penetrated to 117 ft and never encountered shale. The average depth to bedrock is 73.6 ft, or about 50% greater than above the steep slope band. However, the 3 boreholes nearest to the Pinedale glacial limit (PZ-12 thru 14) average 88.3 ft to bedrock. Thus, near the glacial limit there are till deposits up to 40-50 ft thick that are absent above the steep slope band, and thinner in the valley bottom.

The deposits above bedrock are poorly sorted mixtures of porphyry clasts (up to boulder size) in a matrix of weathered gray shale. Based on our 2 backhoe trenches (discussed later), we interpret these deposits as landslide deposits, except where the surface boulders are particularly large and abundant, and where seismic velocities remain low to considerable depths; in those areas we interpret the upper layers as till.

In contrast to the relatively simple water table geometry above the steep slope band (unconfined water perched atop Mancos Shale), the zones of saturation below the steep slope band generally do not coincide with the top of bedrock. Instead, saturated zones occur either within the weathered shale interval (e.g., PZ-11, PZ-15), or above it in the Quaternary deposits. This geometry is presumably related to the increased thickness and diverse textures/ origins of the Quaternary stratigraphic section below the steep slope band, as opposed to above the slope band.

Table 2-5. Depth data from PZs 11-16, SG-3 to SG-5.

GHU	Borehole number	Total Depth (ft below surface)	Depth to Shale (ft below surface)	Upper saturated zone (ft below surface	Lower saturated zone (ft below surface
3	PZ-11	57	42	52-54	
4	PZ-12	90	68	10-40	
4	PZ-13	83	80	34-45	11-27
2	PZ-14	117	Not reached	31-65	
2	PZ-15	46	31	33-45	
5B	PZ-16	55	38	27-31	
5A	SG-3	63.5	63.5	42-?	
5B	I-SG-5	95	76	11-59	
	Mean[1]		73.6		
	Mean[2]		88.3		

[1] all boreholes
[2] boreholes in till zone (lateral moraine) only

2.5.5 Landslide Trenching

We excavated two trenches on the East Slide to examine the downslope margins of two of its polygons. The upper trench was across the contact between the young-looking middle of the landslide (polygon 36, Qlsy) and the older-looking lower 1/3 (polygon 34, Qlsiy). Irish (1996) mapped this scarp as the toe of the East Slide with unfailed till underlying the slope to the SE. In contrast, RCE (1995), Baum (1996), and USFS (2006) placed this scarp within the East Slide. The lower trench was across the toe of the East Slide, as mapped by RCE (1995), Baum (1996), USFS (2006), and this report (Plate 1).

2.5.5.1 Upper Trench

This trench was excavated to expose the structure beneath the boundary scarp separating polygon 36 (Qlsy) from polygon 34 (Qlsiy). This linear SE-facing scarp trends perpendicular to the landslide axis and is about 45 ft high (marked with an “e” for eroded scarp on Plate 1). Based on our airphoto mapping, and on the discrepancy between previous mappers (see above), it was unclear to us whether this scarp (Fig. 2-24) was a headscarp formed by the lower 1/3 of the East Slide (polygon 34) pulling away from the middle (polygon 36), or a toe thrust scarp formed by the middle part of the East Slide overriding the lower 1/3. The rougher surface morphology of the middle part suggested the latter origin. Obviously, the nature of the contact had to be determined in order to draw the stability cross-section (Chapter 8), and to assess where reactivation would express itself if it did occur in the future.

Prior to trenching, we surmised that if the scarp was the headscarp of polygon 34 pulling away from polygon 36, it would be underlain by a normal fault and other extensional deformation (Fig. 2-25). Conversely, if the scarp was the toe thrust of polygon 36 overriding polygon 34, it would be underlain by a reverse fault and other compressional deformation. In addition, the 10 ft-deep trench would expose landslide deposits in the walls and permit us to describe their texture, stratigraphy, and internal deformation, something that is not possible to do from examining split-spoon samples.

Stratigraphy: The trench exposed massive Quaternary landslide deposits that we divided into 3 major units (separated by 2 reverse faults) and 10 facies subunits (Fig. 2-26). The youngest major unit (unit Qls1) comprises the southern half of the trench (0-14 m on the horizontal scale, Plate 3). We infer it is the youngest landslide deposit, because it appears to be on the footwall of both landslide toe thrust structures. Unit Qls1 is divided into a shaly facies (Qls1b) in the middle of the trench and a mixed clayey and sandy facies (Qls1a) farther south. The shaly facies is composed mainly of deformed blocks of Mancos Shale, which are generally not individually delineated on the trench log (Fig. 2-26). These blocks are up to 3 m long and 2 m thick, although the average size is much smaller. Within individual shale blocks the bedding is consistent, but some blocks are folded, such as the one between 10m and 13 m on the horizontal scale. This folding is presumably caused by compressive stresses in the footwall generated

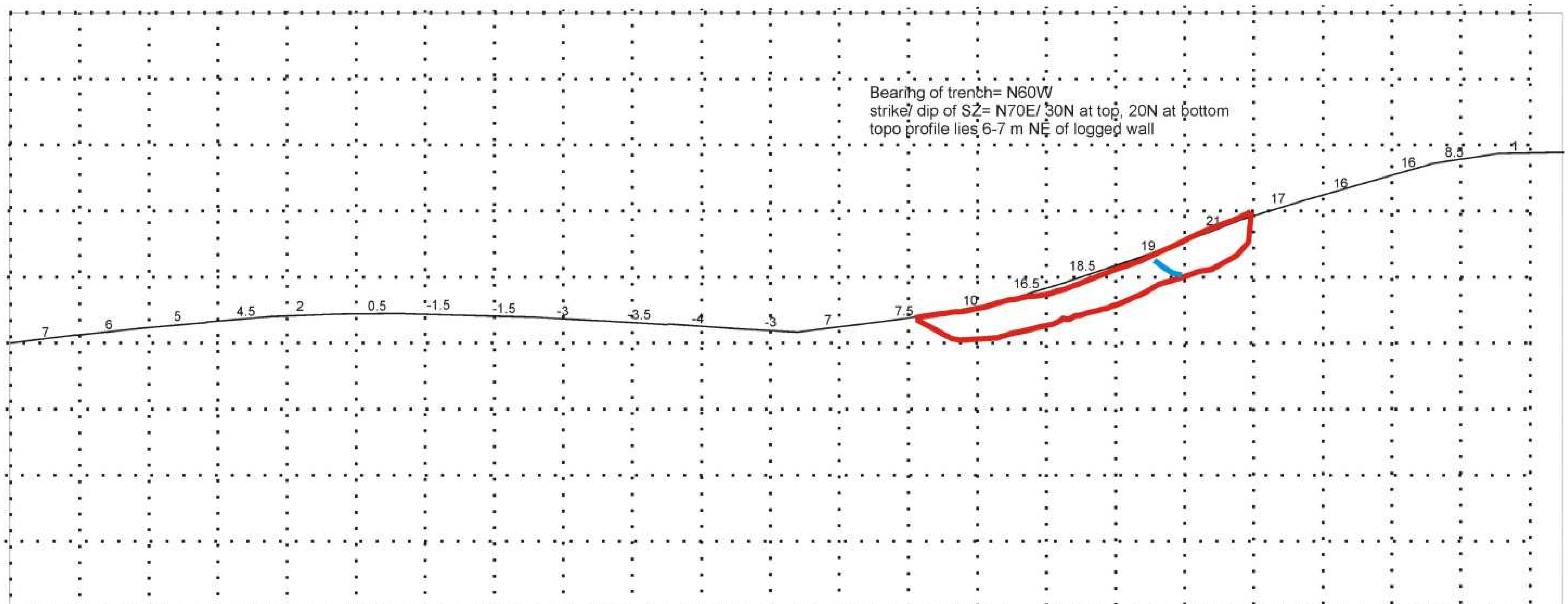


Fig. 2-24. Topographic profile across the boundary scarp between the middle of the East Slide (Qlsy polygon 36) and the toe area (Qlsiy polygon 34). Northwest is to the right. Trench outline is shown in red, with the upper reverse fault shown in blue. More distributed shear and compression is evident in the middle 1/3 of the trench (see Fig. 2-18).

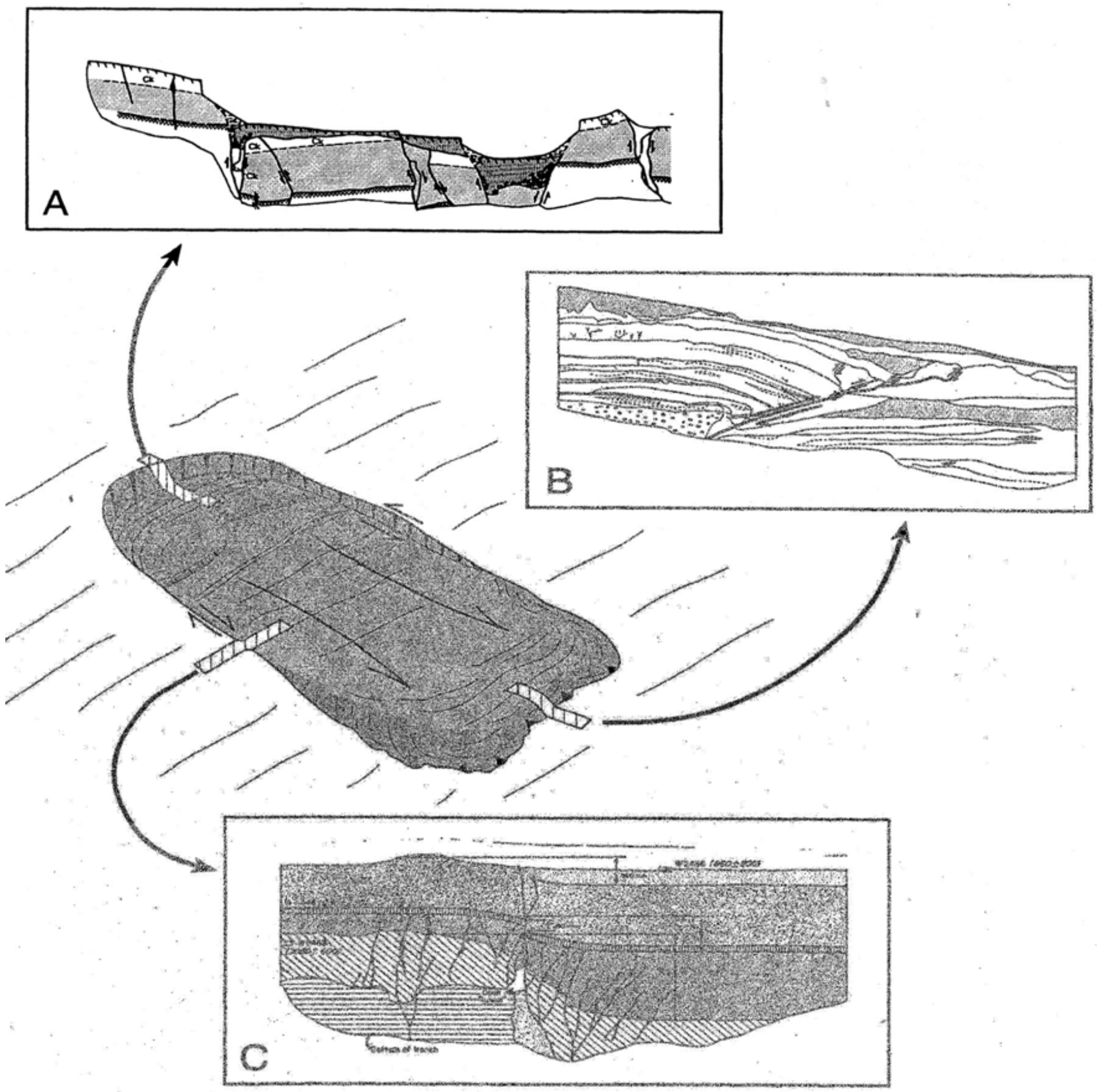


Fig. 2-25. Conceptual diagram showing what type of structures should be found in trenches across landslide margins. A, normal faults and grabens at headscarp (trench log from the Borah Peak normal fault rupture); B, reverse fault at toe; C, strike-slip fault at margin, example form Borrego Mountain, CA rupture. From Cotton, 1999.

UPPER TRENCH
Log of southwest wall, Sheet 1 of 3 (0-8 m)
Snodgrass Mountain
Crested Butte Mountain Resort

GEO-HAZ Consulting
July, 2007

Explanation:

QswAC Slope wash deposit, brown to dark brown, loose to medium dense, gravelly sand to silty sand, contains A horizon organics in upper zone. Note that white paint line delineates the bottom of a zone of loose, bioturbated (highly burrowed) soil. This line was not painted on the remainder of the trench wall since it was not related to landsliding.

Qls1a Landslide deposit 1, mixed clayey and sandy facies, diamicton containing cobble-sized shale and porphyry clasts in a sandy clay matrix.

Qls1b Landslide deposit 1, shaly facies, composed of deformed boulders of Mancos Shale, which have not been individually delineated on the log. No porphyry clasts.

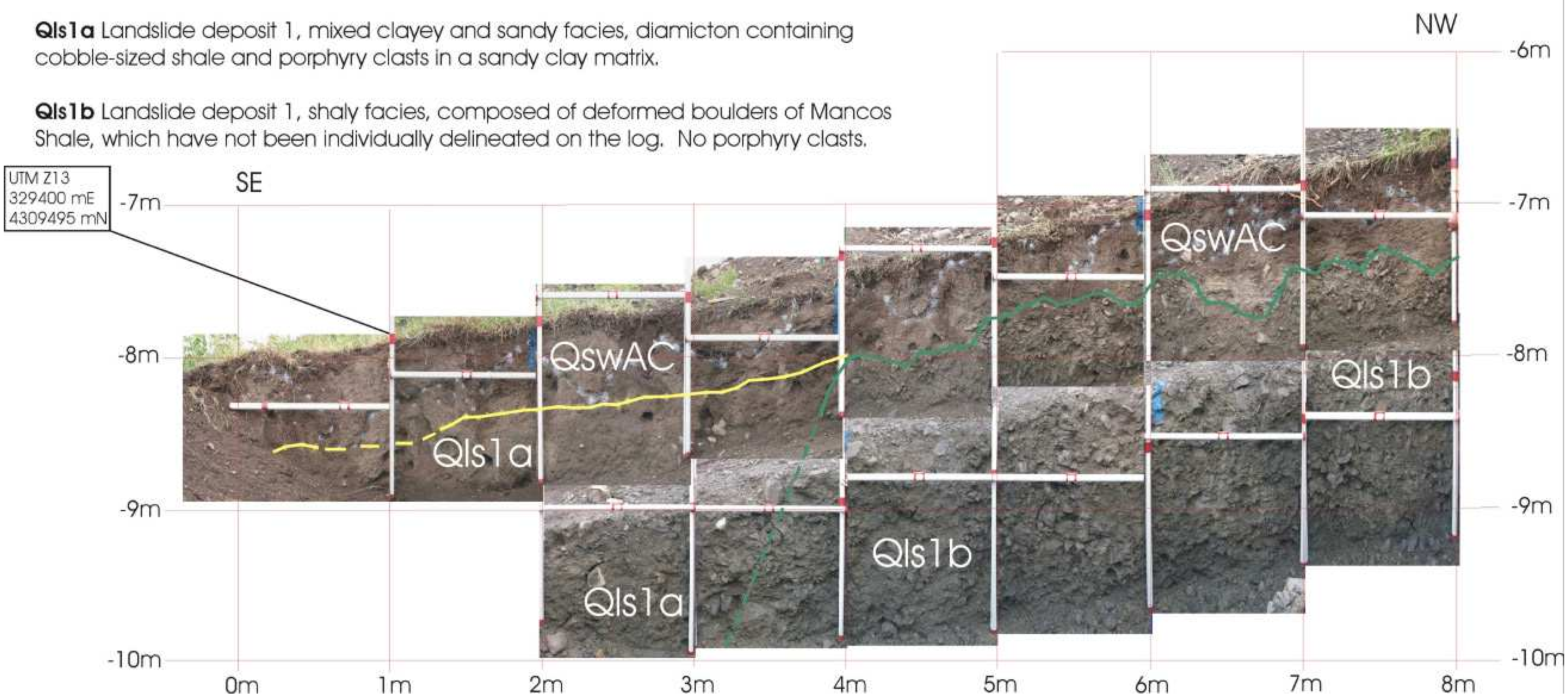


Fig. 2-26a. Log of the west wall of the lower 1/3 of the Upper Trench. Rectified photomosaic made with standard methods. See text for descriptions of map units and structures.

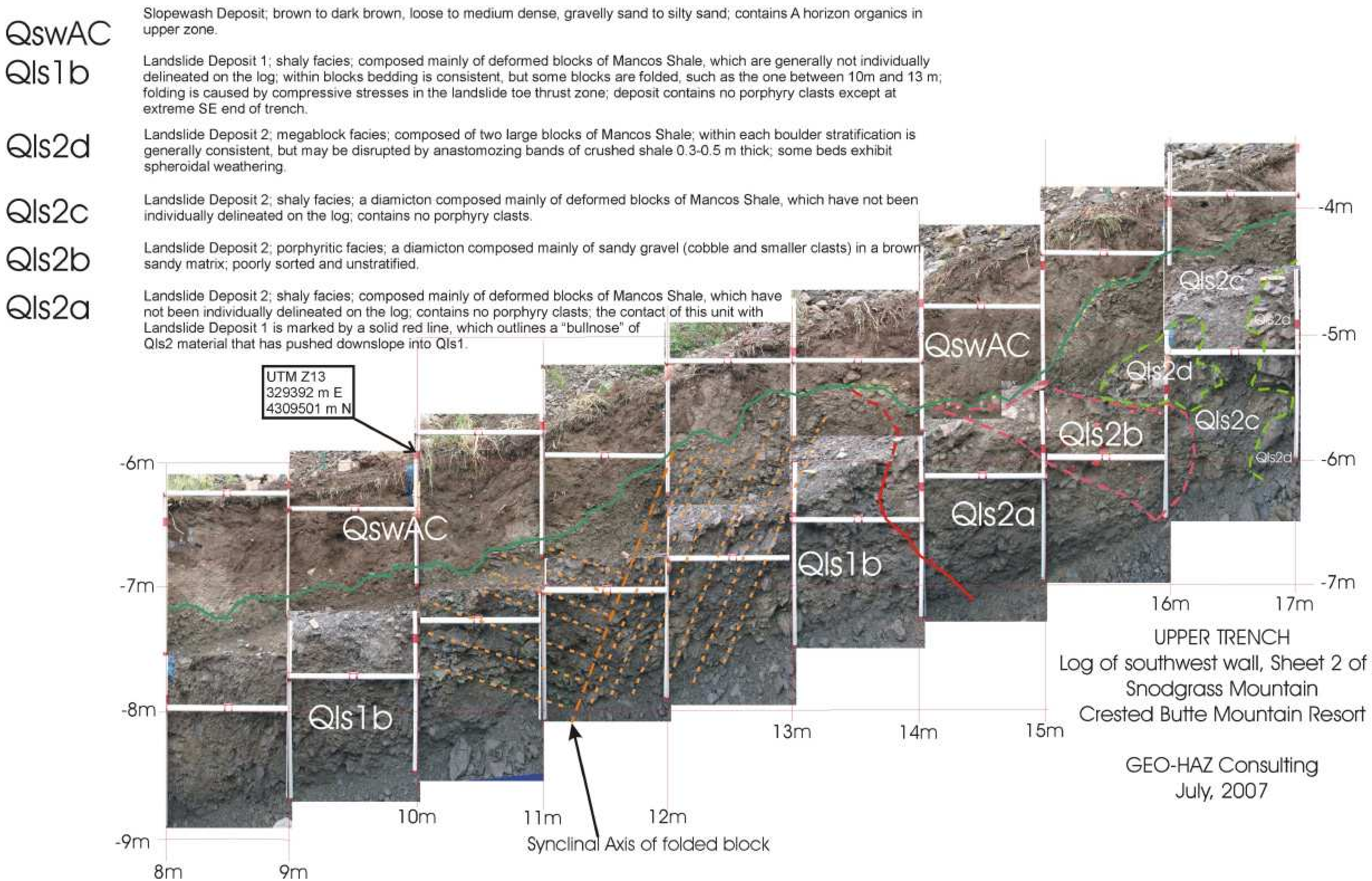


Fig. 2-26b. Log of the west wall of the middle 1/3 of the Upper Trench. Rectified photomosaic made with standard methods. See text for descriptions of map units and structures.

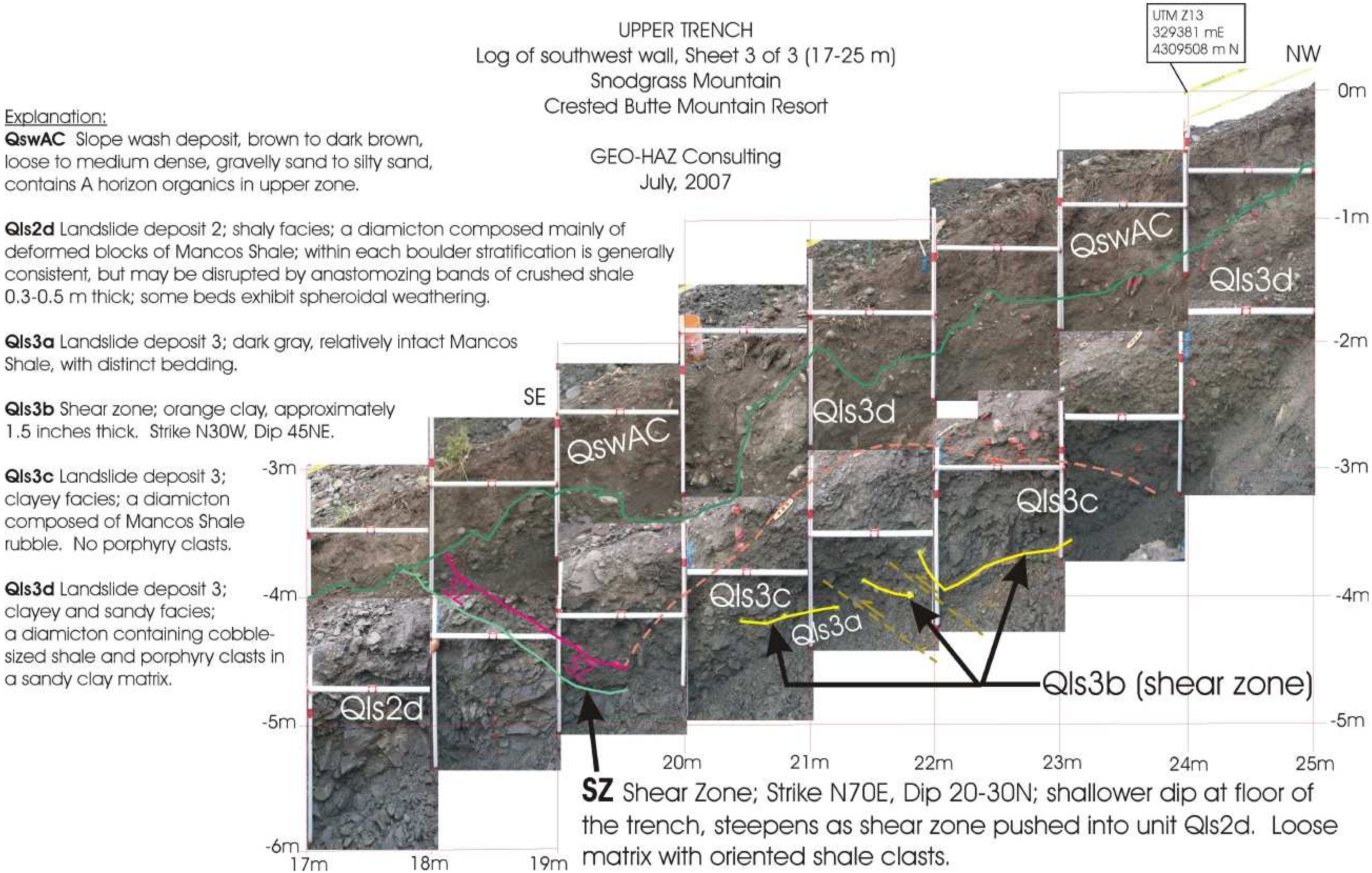


Fig. 2-26c. Log of the west wall of the upper 1/3 of the Upper Trench. Rectified photomosaic made with standard methods. See text for descriptions of map units and structures.

by overriding on the hanging wall. The subunit contains no porphyry clasts except at extreme SE end of trench. The mixed clayey and sandy facies (Unit Qls1a) is a diamicton containing cobble-sized shale and porphyry clasts in a sandy clay matrix. This facies contains no large intact blocks of shale, and looks to be a churned mixture of Mancos Shale and porphyry material.

Deposits between the two reverse faults (red lines on Fig. 2-26 and Plate 3) are grouped into unit Qls2, subdivided into 4 facies. Subunits Qls2a and Qls2c are shaley facies similar to unit Qls1b, and contain deformed blocks of Mancos Shale in a ground-up shale matrix; porphyry clasts are absent. Unit Qls2b is a porphyritic diamicton composed mainly of sandy gravel (cobble and smaller) in a brown sandy matrix, poorly sorted and unstratified. Unit Qls2d is a megablock facies of Qls2c. This unit is composed of two large blocks of Mancos Shale within which shale stratification is generally consistent from one end to the other, but cut internally by anastomozing bands of crushed shale 0.3-0.5 m thick (zones of distributed shear).

Deposits upslope of the upper reverse fault (from 19m to 25 m on the horizontal scale) are grouped into major unit Qls3. Assuming that thrust movement has placed older deposits over younger, this is the oldest major unit in the trench. Unit Qls3 is divided into 4 facies units. At the trench bottom, the top of apparently intact Mancos Shale is exposed beneath a thin, orange-stained shear-and-alteration zone. Drilling and geophysics indicate that the top of in-situ shale is much deeper than the trench floor, so unit Qls3a is probably the top of a large displaced block of Mancos Shale. The shear zone of Qls3b is a zone of orange clay about 1.5" thick. This unit was sampled for direct shear testing. The remainder of Unit Qls3 is composed of a lower clayey facies (Qls3c) and an upper sandy facies (Qls3d). In the former there are no porphyry clasts, whereas in the latter they are abundant.

Overlying all the landslide deposits and underlying the ground surface is a Holocene slopewash deposit that carries an A/AC soil profile (Unit QswAC). Deposition of this unit post-dates formation of the topographic scarp.

<u>Structure</u>: The trench exposed both faults and folds. The two faults identified (red or magenta lines on Plate 3) dip NW, into the slope. The lower fault juxtaposes unit Qls1b on the footwall against unit Qls2a on the hanging wall; both are shaley-facies diamictons, so the fault is poorly expressed by a weak fabric. The fault is curved into an S-shape, which we believe represents post-faulting folding of an original planar fault (like the upper fault). The upper fault is better expressed, planar, and also dips 20°-30° N. The fault creates a 25-30 cm-thick shear zone that separates unit Qls2b on the footwall from unit Qls3c and Qls3d on the hanging wall. This fault appears to have formed as Unit Qls3 "rode up the back side" of the large block of Mancos Shale that comprises Unit Qls2d.

There are also several folds, both of individual shale blocks and of unit contacts. A shale boulder in unit Qls1b (10-13 m on log) exhibits bedding that defines a sharp syncline within the boulder. This boulder appears to have been folded in the same way as a creased sheet of paper, along a very sharp axis. Directly upslope the lower fault is curved into an S-shape. All four subunits between the two reverse faults (Qls2a-d) have curvilinear, irregular boundaries, as if they had been squashed into each other and sheared. There is even a detached piece of unit Qls2d within Qls2c. In the hanging wall of the upper reverse fault, the contact of units Qls3c and Qls3d is arched up in the hanging wall. Beneath this arch, the thin shear zone (unit Qls3b) has been dismembered into separate pieces, as if two minor N-dipping reverse had displaced it (dashed lines on Plate 3). Such inferred reverse faults might be expected to form in the core of a rollover hanging wall anticline.

<u>Interpretation</u>: All of the structures observed in this trench are compressional, that is, folds and two faults that dip northward. We cannot definitively prove that these two faults have reverse displacement, because units across them cannot be correlated. But the correspondence of folding with faulting, and the compressional deformation of individual shale boulders, argues that all the deformation exposed in the trench occurred in a compressional stress field. In contrast, there are no extensional structures in the trench, such as normal faults, grabens, or fissures. Thus, the trench structures indicate that this scarp was formed by the toe of polygon 36 overriding the terrain to the south.

To assist in visualization of the entire deformation pattern, a composite trench log is shown at 24”x48” size in Plate 3.

<u>2.5.5.2 Lower Trench</u>

This trench was excavated to expose the structure beneath the southern edge of polygon 34 (Qlsiy), which most mappers (e.g. Gaskill et al, 1991; RCE, 1995; Baum, 1996) mapped as the toe of the East Slide. The trench was located near the eastern edge of the mapped toe, just above the eastern marginal stream that flows down the east side of the East Slide. We expected to find one or more north-dipping toe thrusts in the trench

<u>Stratigraphy</u>: The trench exposed massive Quaternary landslide deposits, which we divided into 3 major units separated by 2 thrust fault zones, as in the Upper Trench. The youngest unit (Qls1) occupies the lower half of the trench (Fig. 2-27a). This unit is subdivided into a lower clayey facies (Qls1a) and an upper sandy facies (Qls1b). The clayey facies is a diamicton containing clasts of only Mancos Shale, cobble- and gravel-size; the matrix is clay, with a uniform gray color, derived from Mancos Shale. The sandy facies is a diamicton containing rare boulders of porphyry up to 1 m long; the matrix is sandy clay, with a mottled color (yellow-white-brown), derived mainly from porphyry.

Between shear zones SZ1 and SZ2/3 we define an intermediate-age landslide deposit, Qls2 (Fig. 2-27b). This deposit is a diamicton containing cobbles of porphyry up to 25 cm long; the matrix is sandy clay, with a mottled color (yellow-white-brown), derived mainly from porphyry.

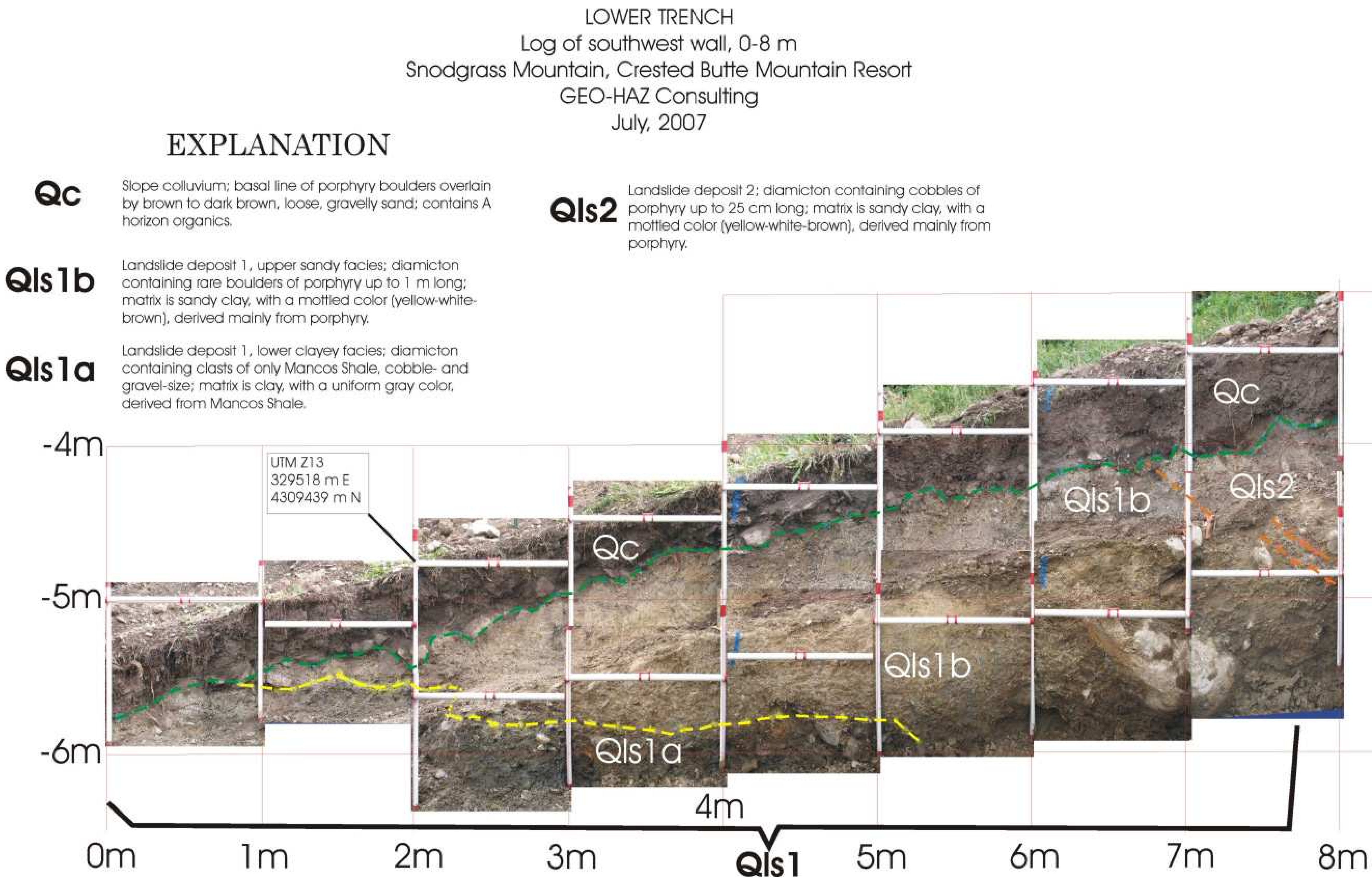


Fig. 2-27a. Log of the west wall of the lower half of the Lower Trench. Rectified photomosaic made with standard methods. See text for descriptions of map units and structures.

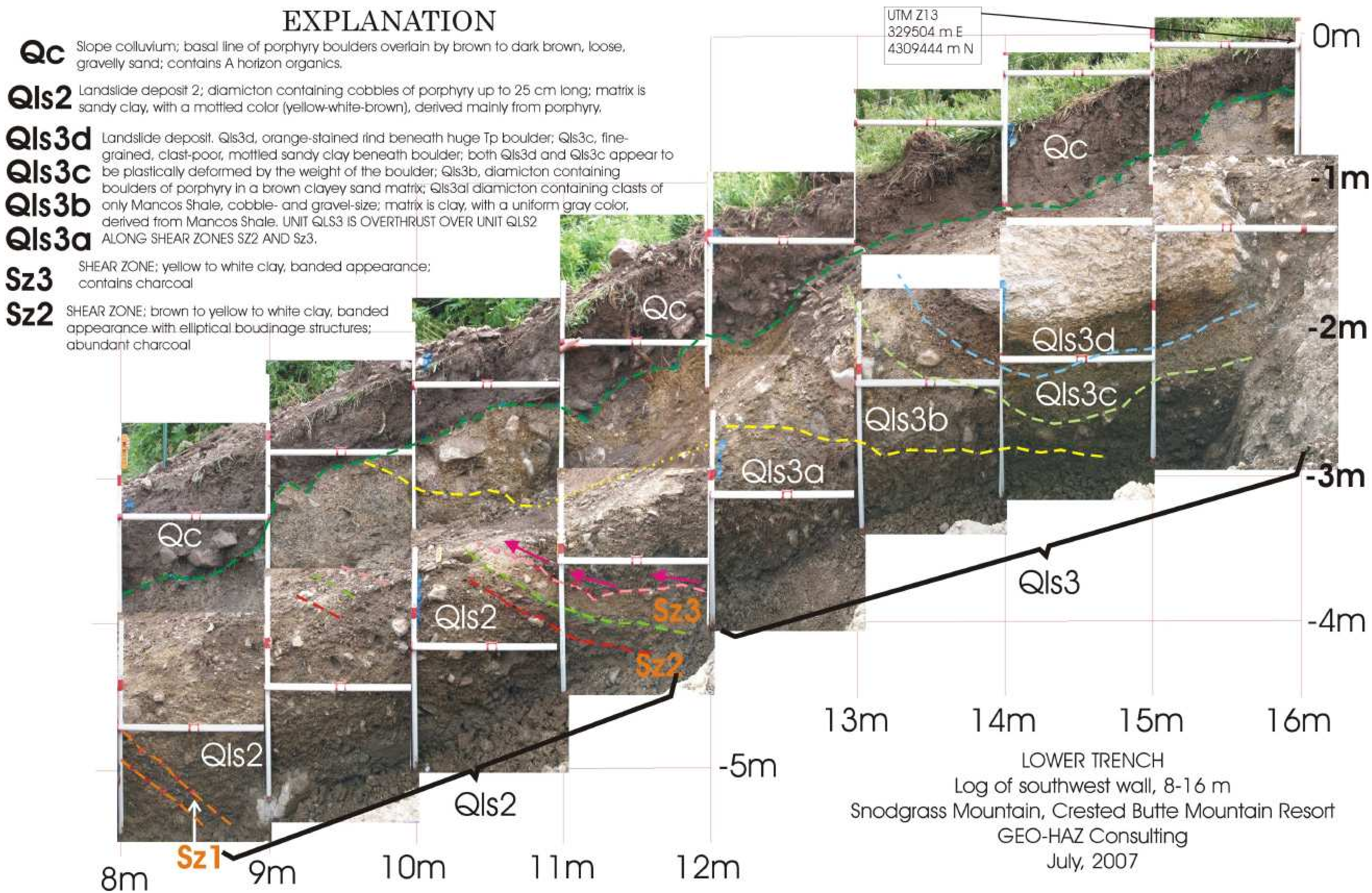


Fig. 2-27b. Log of the west wall of the upper half of the Lower Trench. Rectified photomosaic made with standard methods. See text for descriptions of map units and structures

The upper ¼ of the trench exposes the oldest (?) unit, Qls3. We subdivided this landslide deposit into 4 subunits. The oldest (Qls3a) is a diamicton containing clasts of only Mancos Shale, cobble- and gravel-size; matrix is clay, with a uniform gray color, derived from Mancos Shale. Unit Qls3b is a diamicton containing boulders of porphyry in a brown clayey sand matrix. Qls3c is a fine-grained, clast-poor, mottled sandy clay beneath a huge Tp boulder. Qls3d is an orange-stained "rind" beneath the boulder. Both Qls3d and Qls3c appear to be plastically deformed by the weight of the boulder.

Structure: Like the Upper Trench, the Lower Trench exposes 2 groups of shear zones that dip at a shallow angle into the slope. These shear zones are somewhat better defined than the ones in the Upper Trench. SZ1 is a relatively vague zone of diamicton with a weak-moderate shear fabric dipping toward the head of the trench. Shear zones SZ2 and SZ3 are the lower and upper half of a single 40 cm-wide shear zone that also dips upslope. SZ2 is a brown to yellow to white clay, with banded appearance and elliptical boudinage structures; it contains abundant charcoal. SZ3 is a yellow to white clay with banded appearance and contains less charcoal. The sharp boundaries of these 2 zones and their internal shear structures and fabrics indicate they are fault zones, but the correlation of units across them is not clear.

Interpretation: As in the Upper Trench, the Lower Trench is composed of several facies of landslide deposits, some of which contain only Mancos Shale, others only Tertiary porphyry. The trench is dominated by shear zones SZ2 and SZ3, which form a well-expressed zone of thrust faulting. This thrust fault contains abundant charcoal which is not present in any other unit. Thus, we infer that the toe of the East Slide (polygon 34) slid southward atop SZ2/3 and advanced across a burned ground surface, incorporating and mixing burned material into the basal shear plane. A radiocarbon date on this charcoal is pending. Based on the local geomorphology and our interpretation of the Upper Trench, this toe thrust of polygon 34 would be older than the toe thrusting of polygon 36 exposed in the Upper Trench.

2.6 Deep-Seated Gravitational Spreading (Sackung)

The Snodgrass laccolith is a smaller version of the Mt. Crested Butte laccolith, and the latter is heavily affected by fracturing and splitting of the edges, due to gravitational spreading. This phenomenon, known as "sackung", results from the weight of the heavy laccolith rocks forcing horizontal extrusion of soft Mancos Shale out from around the edges (Fig. 2-28). Where the Mancos Shale is being extruded around the edges, the overlying laccolith rocks are placed into an extensional stress field, which leads to fracturing, splitting, and foundering of the edge-blocks.

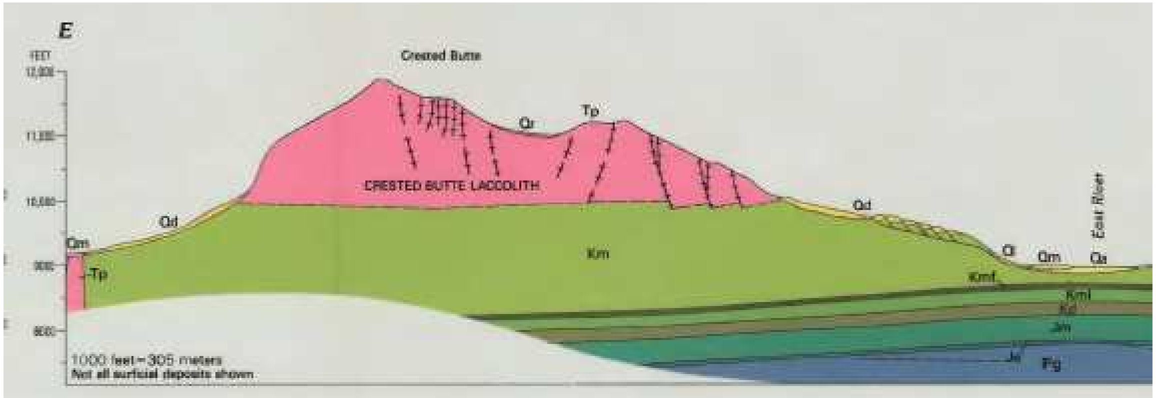


Fig. 2-28. Geologic cross-section through Mt. Crested Butte. This is the western half of cross-section E-E' of Gaskill (1991), which trends SW-NE. Note that beds in the Mancos Shale (Km) are bent into a weak syncline below the laccolith. Subvertical lines in the laccolith with cross-tics indicate sackung faults, along which the Crested Butte Laccolith is breaking up and differentially settling down into the ductile Mancos Shale. Settling is most severe on the eastern side. At the far left edge of the cross-section, the vertical contact between Tp and Km is located near the long, regional NW-trending fault that projects NW-ward along the sharp western edge of Snodgrass Mountain (Fig. 1-4).

So far, we have not identified any evidence of sackung on Snodgrass Mountain, which is about 1000 ft less high than the Mt. Crested Butte laccolith. It may be that, being thinner, the Snodgrass laccolith does not weigh enough to generate this lateral spreading process.

However, there are several linear valleys or alignments of topographic saddles that may represent incipient sackung formation. The former valleys lie at the head of the East Slide, the larger valley of which is truncated by the east margin scarp of the Middle Slide Complex. The latter alignments are best expressed at the crest of the steep slope band just east of the axial stream. Here, a closed depression has formed (polygon 23, Qlsy) along the eastward projection of a linear trough to the west. It appears that this depression was created by piping of surface sediments into open fractures, which formed as the crest of the steep slope band pulled southward away from the rest of the slope.

2.7 Summary of Landslides on the SE Side of Snodgrass Mountain

We believe that the widespread occurrence of deep-seated bedrock landslides on the SE side of Snodgrass Mountain results from the spatial juxtaposition there of 3 unfavorable factors (stratigraphic, structural, and erosional).

Stratigraphic factor: At the contact between the laccolith and the underlying Mancos Shale, there is a transition zone ca. 100 ft thick of thin sills of Tp interlayered with thin beds of Km. The transition zone combines two conditions that favor landsliding; permeable (fractured) beds of Tp that carry groundwater, with contiguous weak shale beds susceptible to landsliding. This geometry is more favorable for landsliding than either massive laccolith rock or massive Mancos Shale.

Structural factor: The SE flank of Snodgrass Mountain is apparently underlain by a SE-plunging syncline, in which beds of Mancos Shale and the thin sills that parallel them, are bent into a trough that plunges in the same direction as the 8° surface slope, but at a lower (5°) angle. This geometry has two results. Groundwater will tend to travel in fractured thin sills down the axis of the syncline. However, those sills eventually intersect the ground surface (daylight), which forces groundwater to the surface as seeps and springs, both of which are common in the landslide complex.

Erosional factor: During the latest Pleistocene glaciation, ice from the East River glacier spilled through the saddle between Mt. Crested Butte and Snodgrass Mountain. This west-flowing ice eroded the SE flank of Snodgrass Mountain below an elevation of about 9800 ft, which coincides with the middle of GHUs 1B, 3, and 5. We infer that the ice eroded and oversteepened the lower slopes of pre-existing landslides on Snodgrass, causing "daylighting" of strata and groundwater flow in the axis of the syncline. Following deglaciation, this oversteepened scarp began to retrogressively fail upslope, the evidence for which is as follows.

The lower SE side of Snodgrass Mountain is composed of a relatively gentle bench sloping 8° SE (northern half of GHUs 1B and 3, GHU 6) with a steep slope band at its toe. This steep slope band runs NE-SW across the lower face of the mountain between elevations 9750-9900 ft (at its NE end) and 9600-9750 ft (at its SW end). The 150 ft-high slope band averages a 21° slope to the SE, exposes Mancos Shale on its face, and is the site of several springs. This slope band lies just upslope of the lateral moraine, which suggests that it represents a failure related to glacial oversteepening along the latest glacial trimline.

Since deglaciation, parts of the landslide complex have continued to move, as indicated by the young geomorphology of the Qlsy and Qlsh polygons. The exact trigger mechanism for this Holocene movement is unknown, but is probably increased precipitation leading to increased pore-water pressures. Earthquake shaking is unlikely to be a major trigger, because this area of Colorado exhibits low seismicity and only a few, short, suspected Quaternary faults. As concluded by Bott and Wong (1995), *"Earthquakes referred to are the Aug-Sept. 1986 Crested Butte earthquake swarm that occurred 20 km to the N45W from Crested Butte."* The swarm contained 200 earthquakes, 30 of which were ML 1.6 or greater, and 16 were reported felt. The largest event, ML 3.5, occurred on 3-SEPT-1986. Bott and Wong (1986) ascribe the swarm to movement on the "Treasure Mountain fault" (informal name), the only Neogene fault mapped in this area by Kirkham and Rogers (1981). The fault is 4 km long, dips steeply to the NE, and displaces Tertiary volcanic rocks. And as explained in the following section, there have been landslides nearby that were not synchronous with any earthquake activity.

2.8 Summary of Landslides elsewhere in the vicinity

There is little written documentation of the timing and amount of landslide movement in the area surrounding Snodgrass Mountain. An anecdotal statement by Western Engineers (1986, p. 8) states: "*Two recent winters [1984, 1985] with heavier than normal precipitation have caused significant instability in nearby areas on slopes underlain by Mancos Shale such as at the reservoir site. Many small-magnitude earthquakes have shaken the Crested Butte area in the last two months.*" However, that report contains no further details or map of the "significant instability", and no evidence of such activity appears on the 2004 airphotos, so we cannot locate it. However, there are three areas of historic (or probable historic) landslides in the vicinity of Snodgrass, which are fresh enough to use as modern analogs for possible landslide reactivation on the SE slope of Snodgrass.

2.8.1 Two Landslides South of Snodgrass Permit Boundary

The reservoir site referred to by Western Engineers (1986) lies at the toe of the southeastern slope of Snodgrass Mountain, where a narrow ridge of Mancos Shale constricts the stream flowing west out of the Snodgrass-Crested Butte saddle. The slopes above the damsite contain the youngest-looking landslides in the area, which lie just south of the Snodgrass permit boundary. These 2 landslides (mapped by Gaskill et al., 1991; see Fig. 2-5) occupy a section of slope underlain by Mancos Shale that was oversteepened to 17-21° by erosion of the spillover ice lobe.

These landslides do not appear to be shallow (6-8 ft thick) debris slides that transformed into debris flows, because their headscarps are high, the bodies are back-rotated, and there are no fluid debris flow toe deposits. Instead, they look like soil slumps. Despite the apparent young appearance of these 2 landslides (unvegetated headscarps, sharp hummocky topography), the landslides are clearly visible on the 1951 aerial photographs. Thus, they are at least 56 years old. Nothing else is known about them.

2.8.2 Gold Link Slide-Flow Failure on Mt. Crested Butte

The only historic failure for which we have good data is the 22-MAY-2001 landslide on the Gold Link trail of the Crested Butte ski area. Two reports were made on this landslide, one by the USFS (Hughes, 2001) and one by a consulting company hired by CBMR (CTL Thompson, 2001); both reports are contained in Appendix 2.1, along with many photographs and sketches of this failure. According to Hughes (2001*), "The slump appears to be a shallow debris flow/earth flow situation on about a 30% slope* [17°]. *The result of this earth flow has left a scar about 60 ft. wide, 6-8 ft. deep, and 200 ft. long.* [Corresponding values from CTL Thompson were 20-65 ft wide, 5-8 ft deep, 280 ft long]. *The amount of material displaced was estimated by Stewart Johnson to be roughly 4,000 cu. yds. This displaced material flowed, mostly as a fluid, down slope for roughly another 200-250 ft. The flow split 1/3 of the way down slope and followed 2 small drainage ways to the base of the slope. The western most flow washed up against the base of tower 4 and bent the base of the ladder, and left* *an accumulation of material, but did not appear to have any other visible impact."* Based on the above description, the landslide would be classed as a debris flow-debris slide (or "flowslide") failure (Fig. 2-29).

Fig. 2-29. Distant photograph of the 22-MAY-2001 Gold Link landslide (at center) in the Crested Butte ski area, looking south toward Mt. Crested Butte.

Hughes (2001) goes on to say: "*The displaced material appeared to be colluvium from mixed sources with a loamy texture with rounded cobble and stone in the matrix. The USGS, "Geologic Map of the Gothic Quadrangle, Gunnison County Colorado, Map GQ-1689, 1991,"* [Gaskill et al., 1991] *identifies this area as "Qu", an undifferentiated unit consisting of colluvial slope wash from mixed sources, including glacial material as being on the upper part of the slope, and the lower part of the slope as being Mancos Shale, with glacial material on top of it in spots. This map also identifies slump scarps and some earth flow patterns or lobes in this vicinity. I observed these features on site and determined that this earth flow is actually an earth flow within an older earth flow. The current head scarp is just below an older series of head scarps. As I walked directly up-slope, I observed 3 small head scarps and the resultant depressional areas above the current movement area.*" Thus, this failure was apparently a partial reactivation of a preexisting landslide on a 30% slope.

Surprisingly, the 2001 snowpack water content on Mt. Crested Butte was below average (only 89% of the 1982-2005 average for the Mt. Crested Butte SNOTEL site; Table 2-6). Thus, this failure did not occur during an abnormally wet year. By comparison, in the period 1982-2005 (24 years), snowpack was above average in 10 of those years. In 6 of those 10 years (1984, 1985, 1986, 1993, 1995, 1997, 1999), the snowpack was more than 110% of normal. Therefore, in 1/4 of the 24 years between 1982 and 2005, the natural amount of snowmelt water available on Mount Crested Butte was more than 10% above average. Although there are many ancient landslide deposits in the Crested Butte ski area, none were reactivated during those 6 years that experienced >10% more snowmelt.

Table 2-6. Snowpack water content, 1982-2005, from the Mt. Crested Butte SNOTEL site.

Year	% of Average Snowpack
1982	109%
1983	92%
1984	143%
1985	112%
1986	128%
1987	88%
1988	86%
1989	90%
1990	81%
1991	94%
1992	92%
1993	123%
1994	78%
1995	138%
1996	103%
1997	124%
1998	82%
1999	114%
2000	85%
2001	89%
2002	71%
2003	93%
2004	80%
2005	107%

Compared to the Gold Link failure site, the southeastern slope of Snodgrass Mountain is generally less steep than 30% [17°] slopes (Fig. 2-30). Slopes steeper than 17° dominate the upper half of the West Facet (GHU 1A), the head of the East Slide (GHU 5A), and the steep slope band (Fig. 2-30a). Similar steep slopes comprise all of GHU 8 and most of GHU 7 (The East Facet; Fig. 2-30b). Slopes on the remainder of Snodgrass's SE slope (GHUs 1B, 2, 3, 4, 5B, and 6) mainly have slope angles less than 17°. Therefore, using the analogy of the Gold Link failure, and given the probability that Snodgrass colluvium is similar to that on Mt. Crested Butte, we can assume that there is some potential for similar, shallow, partial reactivation failures on Snodgrass on slopes steeper than 17°. Because of this, in Chapter 8 we calculate the factor of safety for shallow infinite-slope type landslides on slopes steeper than 17°, as well as for case of full-reactivation of deeper (40-60 ft) ancient landslides.

On those slopes of 17° and steeper on the SE slope of Snodgrass Mountain, particularly on the unforested steep slope band, no failures were observed or reported during snowmelt of 2001, at the time the Gold Link failure occurred. Nor have any failures been observed or reported on Snodgrass during any of the 24 years between 1982 and 2005. This lack of observed activity suggests that groundwater fluctuations during those years were insufficient to trigger the type of highly visible, slide-flow failure that occurred at Gold Link in 2001. This was true even in 1984, when snowpack was about 143% of normal, and in 1995, 138% of normal.

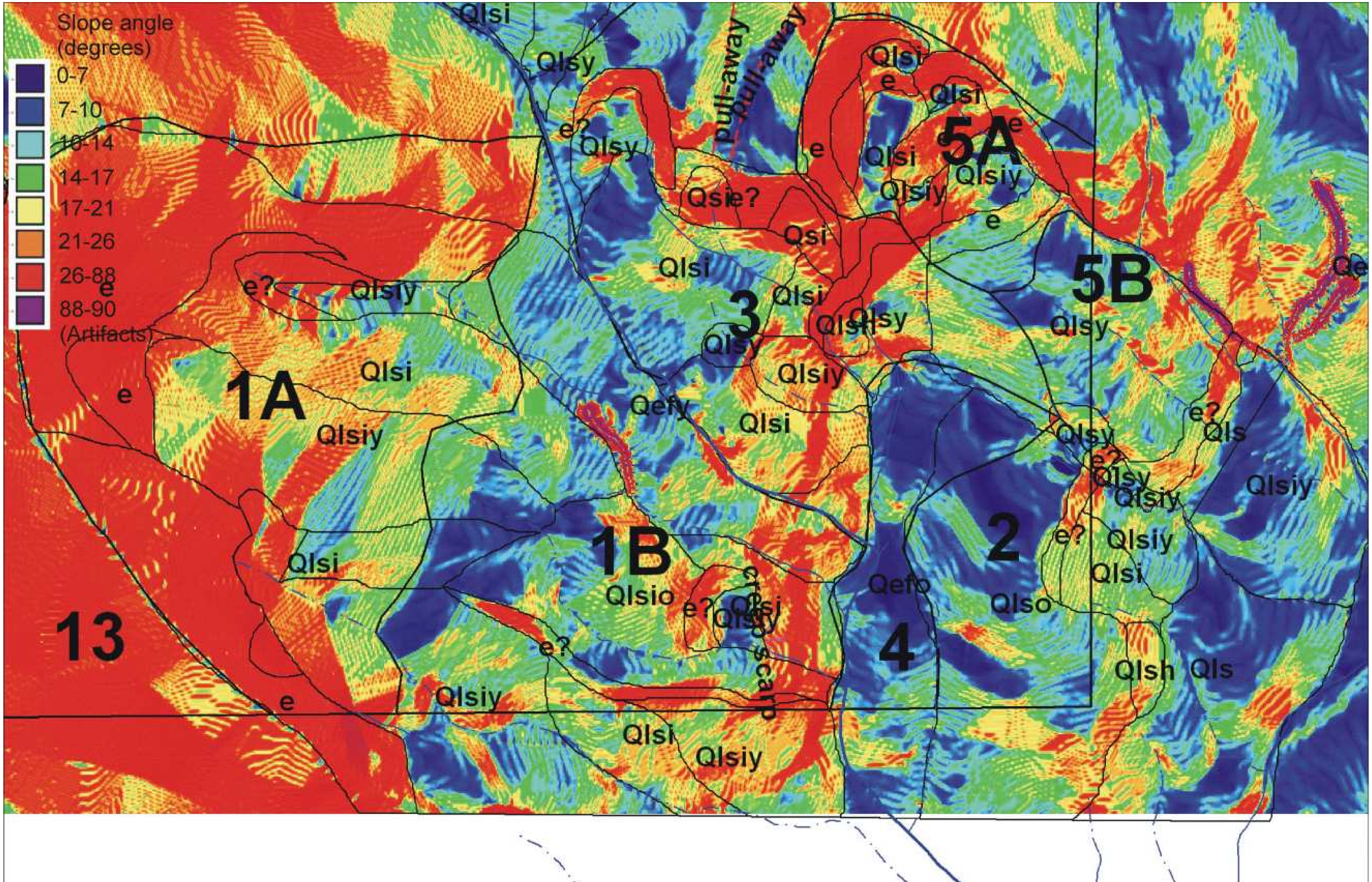


Fig. 2-30a. Slope map of GHUs 1-5 on the SE slope of Snodgrass Mountain.

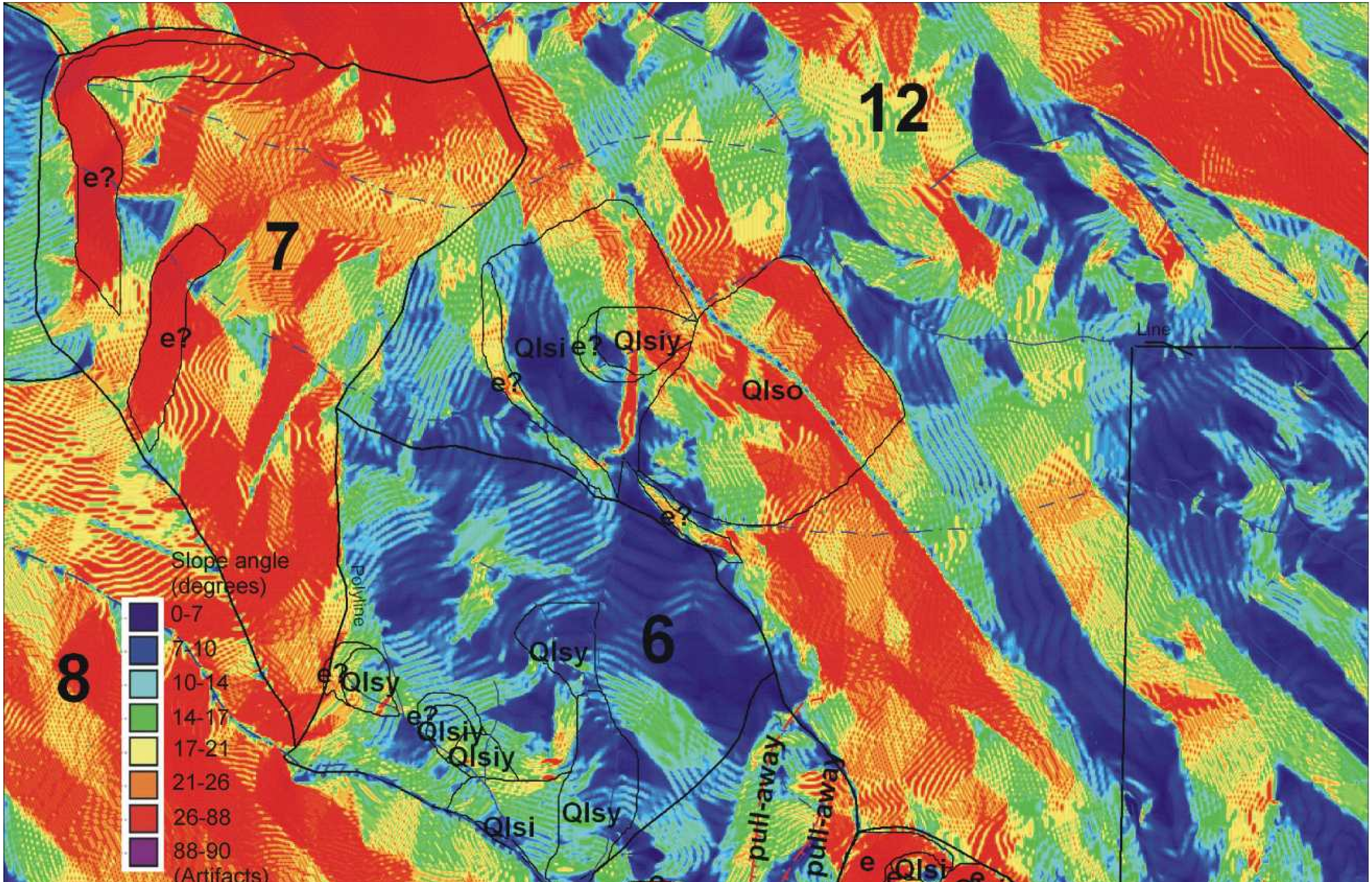


Fig. 2-30b. Slope map of GHUs 6-8 and 12 on the SE slope of Snodgrass Mountain.

2.8.3 Landslide on the East Fork south of Gothic

Fig. 2-31 shows a fresh-looking landslide on the east bank of the East River between Snodgrass Mountain and Gothic. The photograph was provided by USFS personnel and the exact location of this landslide is unknown to the author. This landslide has not been located on the 1951 or 1967 airphotos, so we do not know if it is historic, although it looks like it could be.

Fig. 2-31. Photograph of a fresh-looking slide-flow failure (center) on the eastern side of the East Fork, somewhere between Snodgrass Mountain and Gothic.

The valley floor in this area appears to be underlain by glacial till, based on the ridgelike landforms above the slide, and the abundant boulders visible on and below the headscarp. There are several morphologic features of interest. First, below the headscarp is a hummocky deposit composed of light-colored boulders (porphyry?) and dark matrix (derived from Mancos Shale?). This deposit climbs up onto the headscarp in the center of the head zone, but does not extend downslope very far below the headscarp. The morphology suggests that this deposit is a thick, rather pasty soil slump derived from till composed mainly of ground-up Mancos Shale. Second, below the highest headscarp (right center in Fig. 2-31) there is a smaller hummocky deposit, which transitions downslope into a thin blanket of debris. This blanket extends across the landslide bench and down an escarpment onto the floodplain of the East River. From its shape and extent, this blanket appears to be a debris flow of highly fluid character, much more fluid than the pasty hummocky deposit. One explanation for the pattern here is that the original hummocky slump mass below the highest headscarp had such a high water content at failure, that it partially liquefied and turned into a debris flow. In other words, a similar process to that at Gold Link in 2001.

This landslide demonstrates that some high-headscarp and wide-bench landforms may be associated with either a slump process or a debris flow process. In fact, when Irish (1996) studied Snodgrass Mountain, he concluded that the East Slide was not a thick slump at all, but rather a thin mudflow; this, despite borehole information (RCE, 1995) showing a consistent 40-60 ft depth to in-situ Mancos Shale. We do not know what Irish saw that lead him to this conclusion, since there are no fresh, unvegetated debris flow lobes visible today on the East Slide. Perhaps the answer is that slump landsliding is necessary to create the initial high headscarp, but that smaller debris slide-debris flow events can form off the headscarp once it is established.