Review of recent slope stability studies at Snodgrass Mountain, Colorado

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Executive Summary

Snodgrass Mountain, northwest of Mount Crested Butte, Colorado, is the subject of two recent geologic hazards investigations to determine its suitability for ski area development and operation. Slope instability is the primary geologic hazard affecting potential ski area development at Snodgrass Mountain. Reports of these investigations, prepared separately by the USDA Forest Service (2006) and its consultant, and for the proponent, Crested Butte Mountain Resort (CBMR), by its consultant (GEO-HAZ Consulting, Inc., 2008) identify areas of potentially unstable slopes and possible remediation. Areas of greatest concern are the landslide complex on the southeast side of Snodgrass Mountain and steep slopes adjacent to an existing landslide on the northwest side of the mountain. Similarity between surficial deposits at neighboring Mount Crested Butte and Snodgrass Mountain suggests a significant potential for shallow landslides and debris flows or rapid earth flows on Snodgrass Mountain that are similar to those that occurred in 1996, 2001, and 2008 on Mount Crested Butte.

The report by the USDA Forest Service provides an overview of existing conditions, potential landslide problems, and potential mitigation approaches for Snodgrass Mountain. The proponent's report provides a considerable amount of new geological, geophysical, and geotechnical data along with preliminary slope stability analyses and a conceptual design for remedial measures, which consist of surface and subsurface drainage to improve stability of selected landslide areas and a low berm to prevent possible debris flows from impacting two lift towers.

The reports contribute greatly to the base of existing information about geology, hydrology, and slope instability at Snodgrass Mountain, but the data, information, and analyses are inadequate to assure that operation of the proposed ski area will be trouble-free. The available subsurface data leave considerable uncertainty about the primary inputs for slope stability analysis: stratigraphy (geological layering), shear strength parameters of the different layers, and ground water. More deep boreholes and inclinometers are needed. In addition, a longer period of record and more piezometers are needed to understand the complex interactions of surface water and ground water at the site. The relationships between the water table and the basal slip surfaces of the landslides remains undetermined because their actual depths are known at so few locations. These relationships affect the potential for subsurface drainage to improve slope stability. Stability analyses identify some landslide deposits that have great potential for reactivation (low factors of safety) and flaws detected in analyses of some other landslides indicate that their factors of safety may be lower than computed by the proponent. Stability analyses are needed for ground water conditions associated with rapid melting of extreme snow pack for pre- and post-development conditions and for additional landslides and failure modes. Field measurements revealed the low hydraulic

conductivity of surficial deposits at the site, indicating that subsurface drainage measures may have limited capacity to improve slope stability. Consequently, tests and analyses are needed to demonstrate the effectiveness of proposed subsurface drainage remedial measures in reducing ground-water pressures and increasing slope stability. Additional remedial measures (mechanical restraints or avoidance) may be needed if drainage measures prove to be inadequate. Mobilization of Mancos Shale by erosion, landsliding, or debris flow could have severe effects on local aquatic, riparian, and wetland resources by introducing elevated levels of metals and (or) salts into local surface waters. Analyses are needed to assess the potential for landslides originating on Snodgrass Mountain to impact homes in the proposed residential development on the southeast side of the mountain. Remedial measures may be needed to protect the homes.

Depending upon the level of risk of landslide occurrence and damage that is acceptable to the USDA Forest Service, information in the reports can be used as a basis to (1) deny the permit (low risk to facilities and environment), (2) postpone a decision until additional studies have been completed, or (3) accept the proposal and proceed to the Environmental Impact Study to acquire additional data (moderate to high risk). In the event that a ski area is developed on Snodgrass Mountain, monitoring of ground water and slope movement will need to continue throughout the life of the project. Ski facilities will need to be designed and constructed to mitigate for downslope soil creep and landslides.

Introduction

At the request of the USDA Forest Service, I have reviewed two recent reports describing geologic hazards at Snodgrass Mountain, near Crested Butte, Gunnison County, Colorado (fig. 1). These reports were a technical report by the USDA Forest Service (2006) dated October 12, 2006, and titled "Snodgrass Mountain Geologic Hazards and Assessment of Potential Effects of Ski Area Development on Slope Stability" and a consulting report titled "Geology and Slope Stability of the 'Snodgrass Mountain Ski Area,' Crested Butte, Colorado" prepared for Crested Butte Mountain Resort by GEO-HAZ Consulting, Inc. (2008). Throughout the remainder of this report, these will be referred to as the "Forest Service report" and the "proponent's report," respectively. The purpose of this review is to judge the adequacy of these reports for identifying and characterizing existing and potential slope stability problems associated with development of a ski area on Snodgrass Mountain. A large portion of the area on Snodgrass Mountain that is proposed to be developed for skiing lies within the bounds of the Gunnison National Forest. These reports and my review are intended to assist the Forest Supervisor in determining whether to accept the proposal by Crested Butte Mountain Resort to develop a ski area on Snodgrass Mountain and are preliminary to an Environmental Impact Assessment that is required under the National Environmental Policy Act (NEPA).

In conducting this review, I have attempted to do the following: (1) Summarize the concerns and potential slope stability problems associated with ski area development on Snodgrass Mountain. (2) Describe the approach taken in each report, the strengths and weaknesses of each approach, as well as its soundness, adequacy, and appropriateness for the problem. (3) Determine whether all topical and geographic areas of concern or potential concern are addressed adequately by the investigations. This includes identifying any data gaps, inconsistencies, and needs for further analysis. (4) Summarize the findings of each report, and identify areas of agreement, disagreement, and lack of information (data gaps). (5) Suggest actions needed to address deficiencies in the reports. (6) Identify any areas or topics of special concern to consider in the approval process.

Background

A brief description of the site geology, history of the current development proposal, a summary of previous investigations, and the slope stability issues at Snodgrass Mountain and in neighboring areas of western Colorado provide a context for understanding this report.

Site Geology

Gaskill and others (1991) have documented the geology of Snodgrass Mountain (fig. 2). It is capped by a 300-m-thick laccolith of quartz monzonite or granodiorite porphyry that intruded the Upper Cretaceous Mancos Shale. Porphyry sills are interfingered with the shale in a transition zone at the base of the laccolith. Mancos Shale underlies the lower slopes of the mountain, and has been folded into a broad syncline. Glacial activity has modified the slopes and left deposits of moraine on the sides of the mountain. Talus and colluvial deposits cover much of the east and west sides of the mountain. Extensive landslide deposits occupy a crudely semicircular basin at the southeast side and blanket slopes on the south side of the mountain (fig. 2). The topography of landslide deposits within the basin is stepped and hummocky. Scarps on the sides of Snodgrass Mountain indicate shallow slumping in the colluvial, glacial, and landslide deposits (Gaskill and others, 1991).

Current Development Proposal

Snodgrass Mountain is northwest of the existing Crested Butte ski area, and Crested Butte Mountain Resort has proposed to develop a ski area on Snodgrass Mountain in order to provide additional intermediate skiing. The original proposal, made in 1981, was accepted by the U.S. Forest Service (USDA Forest Service, 2006); however, no ski area was developed and subsequent proposals (1994, 2004) have faced concerns about slope stability since the discovery of unstable slopes and landslides on Snodgrass Mountain (Soule, 1976; Gaskill and others, 1991; Resource Consultants and Engineers (RCE), 1995; Irish, 1996; Baum, 1996). The most recent proposal (2004) includes development on parts of Snodgrass Mountain that had not been studied in detail previously. Additional information was also needed for areas that have been studied previously (RCE, 1995; Irish, 1996; Baum, 1996); hence the need for the two recent studies (USDA Forest Service, 2006; GEO-HAZ Consulting, Inc., 2008). The proposed ski area would occupy slopes mainly on the southeastern and northwestern sides of Snodgrass Mountain. Artificial snow derived from surface water pumped from the East River (fig. 1) will be applied to several ski trails. The proponent is also planning residential developments downslope from the ski area on the southeastern side of Snodgrass Mountain, outside the Forest Service permit boundary (fig. 3). Potential may exist for landslides and debris flows or rapid earth flows originating partly or completely on National Forest lands on Snodgrass Mountain to affect the residential areas.

Previous Work

The Forest Service report and the proponent's report summarize the main conclusions of previous studies. The following provides a brief description and highlights important findings of previous reports. Mapping at 1:24,000 scale by the Colorado Geological Survey identified a large number of landslides and unstable slopes on Snodgrass Mountain (Soule, 1976). Gaskill and others (1991) mapped the surficial and bedrock geology of Snodgrass Mountain, also at 1:24,000 scale. These maps identified a large landslide complex on the southeast side of Snodgrass Mountain, as well as other landslide features on the Mountain.

Resource Consultants and Engineers (RCE, 1995) conducted a hydrologic and geotechnical investigation of Snodgrass Mountain. The investigation included mapping of wetlands, detailed mapping of landslide features, geotechnical borings, and installation of piezometers. RCE (1995) concluded that "reactivation of older, smaller slides or activation of new slides may occur as a result of construction and snowmaking operations," on the southeast part of Snodgrass Mountain. They found evidence for past debris flows in the area and expressed concern that ski area development and operations could "have cumulative detrimental effects on long-term stability of the [pre-existing] landslide areas of Snodgrass Mountain." RCE (1995) recommended avoidance or mitigation (subsurface drainage and ground shaping) of the East slide, as well as ground-water and geotechnical modeling and monitoring of landslide areas on the southeast side of Snodgrass Mountain.

Irish (1996) assessed the potential for major landslides on the southeast side of Snodgrass Mountain and concluded that geologic hazards, primarily landslides and expansive soils, might constrain but not preclude development on the southeast side of Snodgrass Mountain. He further concluded that the risk of catastrophic or major failure of landslides on the southeast side of Snodgrass Mountain was low. The risk of small landslides was also considered low, but slightly greater than the risk of major failure. Construction or operational practices that would aggravate the potential for either minor or major failure could be avoided (Irish, 1996).

At the request of the Forest Service, I (Baum, 1996) reviewed the findings of RCE (1995) and Irish (1996) and presented a slightly different interpretation of surficial geology on the southeast side of Snodgrass Mountain based on a brief site visit and study of aerial photography. I concluded that hazards related to debris flow, shallow slumping, and expansive soils can be reduced by detailed, site-specific studies, appropriate engineering, and remedial measures, but that maintenance of the proposed facility might become costly. I considered potential for reactivation of the 1.6-million-m^3 East slide to be serious enough to avoid development and prohibit snowmaking there. I also encouraged detailed subsurface investigation and stability analysis for the major landslide areas on the southeast side of the mountain (Baum, 1996).

Recently, Cotton, Shires and Associates, Inc. (2008) prepared an independent review of the proponent's report for High Country Citizen's Alliance. Their review focused on the southeast side of Snodgrass Mountain and commented on several aspects of the proponent’s methods and results. They concluded that additional geotechnical data and studies are needed to determine the potential for landslide reactivation and recommended additional mitigation and long-term monitoring if the proposed ski area is developed.

Slope Instability at Snodgrass Mountain—The Issues

For the purposes of this report, slope stability issues at Snodgrass Mountain can be subdivided into (1) landslide types and processes and (2) landslide effects. A brief discussion of landslide problems in surrounding areas of western Colorado provides a context and perspective for considering these issues.

Landslide Types and Processes

Landslide Reactivation. Deposits of several large, deep landslides are present on Snodgrass Mountain. Reactivation of one or more of these deposits could cause property or infrastructure damage, and serious environmental degradation. Depending on the rate of movement, reactivation of one of these large landslides has slight to moderate potential for causing deaths and injuries. Reactivation is most likely to occur during spring snowmelt or early summer when ground-water pressure is greatest. Additional water from the melting of artificial snow may raise ground-water pressures above natural levels and increase the probability of landslide reactivation.

Debris Flows. Debris flows or rapid earth flows have occurred in recent years on a neighboring mountain, Mount Crested Butte, which has similar geology and climate to that of Snodgrass Mountain. Shallow translational landslides in the spring of 1996 (J. Burch, USDA-FS, oral commun., 1996), 2001 (J. Burch, USDA-FS, oral commun., 2007; copies of unpublished reports are reproduced in appendix 2.1 of GEO-HAZ Consulting, Inc., 2008), and 2008 (Corey Wong, USDA-FS, written commun., 2008) have occurred, and at least two (1996, 2001) transformed into flows. Rapid snowmelt and intense spring or summer rainfall are contributing factors in occurrence of such slides and flows. At least one previous investigator has reported evidence of rapid flow deposits on Snodgrass Mountain (RCE, 1995); however, the proponent did not find any evidence of these (section 8.4.2, GEO-HAZ Consulting, Inc., 2008). Although debris flows are unlikely during ski season, they move rapidly and have great potential for causing deaths and injuries, as well as environmental degradation and property damage. Debris flows also have great potential to move great distances rapidly, including from National Forest lands to neighboring proposed residential areas.

Rock Fall. Potential for rock fall on Snodgrass Mountain is localized to a few areas of steep rock outcrops. Rock fall can occur in any type of weather and increased rock fall activity is sometimes associated with freeze-thaw. Rock fall is probably the leading cause of landslide-related deaths and injuries and can also cause property damage.

Landslide Effects

Life Safety. Chances of landslide movement are greatest during spring snowmelt and early summer. In addition to ski area maintenance workers present on the slopes at that time, occupants of homes downslope from ski areas may also be present and at risk from injury or death by debris flows or other rapid landslides.

Environmental Degradation. Erosion of landslide and debris-flow source areas and transport zones, ground deformation with attendant changes in surface drainage, and sediment discharge into streams and lakes are the primary forms of environmental degradation resulting from landslides. The effects of sediment discharge may be irreversible. Sediment discharge into areas outside the National Forest boundary is of particular concern at Snodgrass Mountain. Disruption and the erosion of source areas is also a potentially serious problem, because landslide scars in the area appear to require decades, if not centuries to recover. Mobilization of Mancos Shale by erosion, landsliding, or debris flow could have severe effects on local aquatic, riparian, and wetland resources by introducing elevated levels of metals and/or salts into local surface waters (D. Staley, USGS, written commun., 2008).

Property and Infrastructure Damage. Although potential damage to lift lines, utilities, roads, and structures related to ski area development is an obvious concern, property damage from landslides and debris flows impacting residential areas to be developed adjacent to the proposed ski area must also be considered.

Landslide Problems in Western Colorado

Landslides are widespread in western Colorado and many areas, including at least two ski areas (Aspen, Snowmass), have experienced serious landslide problems that include rock falls, debris flows, and large deep landslides (Colton and others, 1976; Rogers, 2003). Most of the large active landslides of western Colorado resulted from reactivation of older landslide deposits; relatively few have resulted from historical first-time failure of weak rock or surficial deposits (Rogers, 2003). Snowmelt is a common factor in debris-flow initiation, as well as in the reactivation of large, deep Colorado landslides, such as the large East Fork landslide in Archuleta County, which reactivated in spring 2008, ruptured a natural gas pipeline, and threatened to dam the East Fork of the San Juan River. Rapid snowmelt has induced dangerous, destructive landslides in 1984, 1985, 2008, and probably will in the future as well (Colorado Division of Emergency Services, 2008). Other factors that contribute to landslide occurrence (Rogers, 2003) include toe erosion resulting from stream cutting (as at the Muddy Creek landslides near Paonia Reservoir, the East Fork landslide, and the Jackson Mountain landslide northeast of Pagosa Springs), excavation (as at Dowd's Junction along I–70 near Minturn), and addition of water to slopes by irrigation or by leakage from pipes and irrigation ditches (as in the North Fork Valley from Hotchkiss to Paonia Reservoir and on the west side of the Cimarron River Valley).

Rates, duration, and cumulative amounts of movement for large Colorado landslides vary considerably. Large catastrophic (sudden and violent) landslides have been uncommon in historical times in western Colorado. Of the three examples of which I am aware, two were first-time rock slides and debris avalanches and the other was reactivation of part of a large landslide deposit near Cameo (Rogers and others, 1992; Noe and others, 2007). Movement rates for large deep landslides, including most clay-rich landslides, are typically slow to moderate (less than 1.8 m/hr; Cruden and Varnes, 1996) although occasional episodes of more rapid movement resulting from elevated ground-water pressure or mechanical loading are possible (Keefer and Johnson, 1983; Kalaugher and others, 2000). For example, the Slumgullion landslide, near Lake City, moves continually with annual displacement ranging from a few centimeters at the head to 6 m at the narrowest part (Fleming and others, 1999; Coe and others, 2003). A large landslide on the west side of the Cimarron River Valley, which is a reactivation of part of a much larger landslide deposit, has moved about 300 m over many years (Rogers, 2003). Reactivation of the DeBeque Canyon landslide in 1958 and 1998 resulted in displacements of several meters in a matter of hours (Noe and others, 2007). Others, such as the earth flows along Colorado Highway 65 on the north side of Grand Mesa, become active for a few weeks in the spring time, move several meters or less and then stop and remain inactive either until the following spring or until another episode of above average snowmelt, years later. For some landslides the time between movement episodes appears to be decades or longer.

Debris flows are also very common in Western Colorado. In contrast to the relatively slow rates for large, deep landslides, debris flows are consistently rapid to very rapid. Although debris flows tend to be more common on steep slopes (30°–50°), they also occur on moderate slopes (15°–30°) and can run out onto very gentle slopes. Debris flows occur in a wide variety of geologic and topographic environments, including moderately sloping surficial deposits on weathered shale, as at Mount Crested Butte. Rapid snowmelt and intense rainfall, either separately or combined (rain on snow) are the most common causes of debris flows in Colorado.

As noted previously, two ski areas are on the Colorado Geological Survey's official list of critical landslides in Colorado (Rogers, 2003). The ski area and local community have been successful in dealing with the landslide, debris-flow, and rock-fall problems at Snowmass. Landslide scarps appeared on the north face of Aspen Mountain in the spring of 1985. Subsequent mitigation significantly reduced the landslide hazard there, but the debris-flow hazard on the west side of Aspen Mountain remains (Rogers, 2003). Other ski areas in Colorado have experienced landslide problems, as mentioned in the proponent's report (GEO-HAZ Consulting, Inc., 2008). Evidently these problems have been less severe than those experienced at Aspen and Snowmass.

The regional snapshot of landslides provided in the preceding paragraphs defines the range of possible outcomes for future landslide activity at Snodgrass Mountain. Large, rapidly moving landslides (greater than 1 million m_ and faster than 5 m/s) are possible but very unlikely in the absence of deep excavation at the toe of the mountain or other major disturbance. Snowmelt-induced reactivation of existing landslide deposits, with slow to moderate rates of movement is possible and more likely than a large rapid landslide. Volumes of reactivated landslides exceeding 1 million m_ are possible (reactivation of the entire 1.6-million-m_ East slide), but smaller volumes (partial reactivation of the East slide, or reactivation of the other landslide deposits) seem more likely. Rock falls are possible and moderately likely at a few steep outcrops on the north side of Snodgrass Mountain. Debris flows also are possible and seem likely, given the proximity of Mount Crested Butte and Snodgrass Mountain and the similar lithologies (Mancos Shale and porphyry) from which surficial deposits on the two mountains are derived. Geologic and climatic conditions and future development actions specific to Snodgrass Mountain will determine whether the landslide deposits remain dormant (or continue deforming very slowly) or any of the aforementioned landslide scenarios occur (large rapidly moving landslides, reactivation of existing deposits, debris flows).

Summary and Analysis of Reports

Forest Service Report

The Forest Service report (USDA Forest Service, 2006) is based primarily upon the work of Michael Burke, a geotechnical engineer formerly with the San Juan National Forest. After Mr. Burke's retirement, the Forest Service contracted with a geotechnical consultant (Buckhorn Geotech, Inc.) to finish compilation of the report.

Approach of Forest Service Investigation

The basic approach was a field-based geologic and geomorphic examination, description, and analysis of Snodgrass Mountain to identify and interpret features that indicate current or past ground movement or potential for future ground movement. The report includes a description of the site geology and a qualitative analysis or classification of landforms observed in the field and on aerial photography and topographic maps. This description is combined with a qualitative assessment of landslide risk associated with ground disturbances resulting from ski area development. The primary purpose of the landform classification was to identify landslide features and other signs of ground movement or potential ground movement and to distinguish their relative ages. Burke subdivided the permit area into geologic hazards units (GHU's) based on contiguous areas having similar landslide features or conditions (fig. 3). Based on his knowledge of Snodgrass Mountain geology and geomorphology, Burke assigned each GHU to a relative landslide age class (active, inactive-young, inactive-mature, or inactive-old, after McCalpin, 1984). Burke assessed qualitatively the risk of landslide reactivation resulting from six activities or conditions associated with ski area development. These are (1) grading, (2) clearing, (3) snowmaking, (4) buried utilities, (5) roads, and (6) lift lines and structures. He considered separately the probability of slope movement with disturbance and the severity of the impact for each activity or condition in each of the 15 geologic hazards units. The assessments were based on "average" effects of the actions, without mitigation.

Strengths of Forest Service Investigation

The report provides a verbal and photographic description of conditions on Snodgrass Mountain that are relevant to assessing slope stability. A map showing locations and directions of photographs improves their usefulness. The report identifies the vast majority of potential problems and problem areas, as well as a range of potential consequences (and mitigation options) from the six major activities related to ski area development. As such, it provides a checklist of what could go wrong with regard to slope stability in each GHU during ski area development and operation. The qualitative risk assessment provides a relative ranking of the seriousness of the potential landslide problems in each GHU that may be helpful in setting priorities for analysis and mitigation.

Weaknesses of Forest Service Investigation

Some parts of the Forest Service report are vague and overly general. For instance, despite the large number of photographs, maps, and verbal descriptions, it is difficult to identify some of the specific areas of concern mentioned in the text. Photographs in appendix C lack captions explaining what the photographs depict. The use of GHU's without plotting specific landslides and other features on the maps also contributes to this difficulty. Although the use of geologic hazards units as presented in this report is a valid approach, a preferred approach is to present data (in the form of a map showing geologic contacts, landslides, faults, zones of soil creep, and so on) separately from interpretation, in this case the GHU's (Hoexter and others, 1978).

Some of the features cited as evidence of slope instability, such as elongated deposits of boulder-sized rocks interpreted to be shear zones, areas of bent or leaning tree trunks interpreted as signs of soil creep, and a series of gentle arcs (concave upslope) defining the boundary between older upslope forest canopy and younger downslope forest canopy interpreted as a possible landslide head scarp (USDA Forest Service, 2006, p. 16–17, 26–27, and 29–30), have other possible explanations (Harker, 1996) so that the accuracy of those interpretations is difficult to evaluate without additional information or carefully observing the features in the field.

Data Gaps, Inconsistencies, and Deficiencies in the Forest Service Investigation

Primary data gaps in the Forest Service report are the previously noted lack of detailed locations for landslide and ground-movement features described from several of the geologic hazards units and the incomplete exploration in GHU 7, 8, 11, 12, and 13, where some features noted on aerial photography, topographic maps, and photographs were not field checked. The need for additional information in these areas depends in part on the amount of disturbance expected there.

Inconsistency between text descriptions and tables makes it difficult to understand how risk levels for the various activities were determined. For instance, it is unclear in table 2 (USDA Forest Service, 2006) why GHU 10B, which contains a sizable active landslide, is listed as unstable slope (US), rather than landslide (LS). Similarly, according to the definitions on page 40 of the Forest Service report GHU 10A should be classified as an unstable slope (US) rather than potentially unstable slope (PUS). The risk assessment for grading and slope shaping (USDA Forest Service, 2006, map 4A and table 3A) seems to contradict some of the discussion in the text for GHU's 1B and 4. As a result of inconsistencies such as these and the use of possible scenarios (what could happen) without any clearly consistent method of determining their likelihood, the risk assessment seems somewhat subjective. While there is certainly a place for applying engineering judgment in dealing with uncertainty, it is not clear that another practitioner would come to identical conclusions.

Main Conclusions of Forest Service Investigation

1. **Active Landslide Areas**. The report identifies two main areas of active landslides along with several other areas of unstable slopes. The southeast part of the permit area on the lower mountain continues to be the area of greatest concern with regard to slope stability. Large landslide complexes (constituting GHU’s 1A, 1B, 2, 3, 4, 5A and 5B) on the southeast side of Snodgrass Mountain show evidence of very slow movement and have moderate to high potential for

accelerated movement. GHU’s 1A, 5A, 5B and 10B have the greatest probability of movement as a result of disturbance. An area on the south part of the west face of the mountain includes an active landslide that is likely to be exacerbated by disturbance (GHU 10B). Areas on the north and east sides of Snodgrass Mountain (GHU 6, 7, 8, 11, and 12) also have moderate to high potential for landslide problems as a result of disturbance. The upper part of the mountain (GHU 9) and west face (GHU 10A) have low to moderate potential for landslide problems.
Comment. Except for minor ambiguities noted in the previous section, the report’s ranking of relative landslide hazard in the various GHU's seems consistent with the data.

2. **Unacceptable Damage**. The report discusses the level at which resource damage would be unacceptable, but the discussion is somewhat incomplete (USDA Forest Service, 2006, p. 68–69). One scenario leading to severe or unacceptable damage, based on a Forest Service criterion for logging and other land uses, is damage to 15 percent or more of a "treatment area." The report concludes that severe damage to the permit area would result in the event of coordinated movement of multiple landslide areas or GHU's comprising at least 15 percent of the permit area. However, the report expresses uncertainty about how the "treatment area" should be defined—the entire permit area or only the portion that is disturbed. Timeframe for the damage is not mentioned, but severe damage might result from cumulative effects over time of many smaller events as well as one large event occurring in a short time. The report further defines impacts as moderate or severe in the case of landslide reactivation or new landslides depending on size or type. Impact of a rapidly moving landslide, such as a debris flow, rock slide, or rapid earth flow would be severe (USDA Forest Service, 2006, p. 69). A large slide or slump (of any speed), occupying 15 percent or more of the "treatment area" would be severe. The number of fatalities, injuries, or magnitude of offsite impacts that would be considered unacceptable is not stated. Offsite impacts were not considered, but the report notes that landslides in the southeast part of the permit area continue offsite, further downslope. For example, the East slide continues downslope toward the edge of the proposed residential development (fig. 3).
   Comment. Clarification of standards, even if only qualitative, for acceptable risk with regard to landslide-related resource damage, injuries and fatalities, and off-site impacts, would facilitate Forest Service decision making and contribute to public confidence in the permitting process.

3. **Mitigation**. The Forest Service report suggests a wide variety of mitigation options to be considered in each GHU for each of the six activities or conditions considered in the risk analysis. The majority of these are site-specific, so summary or analysis of those options is beyond the scope of this report. However, two general recommendations are important and worth emphasizing: (1) the necessity for a mountain-wide drainage plan to mitigate the effects of ski area development and operations, and to protect the many wetlands on Snodgrass Mountain, and (2) numerical modeling of snowmelt infiltration and ground-water flow, in order to analyze the effects of increased meltwater from artificial snow on

slope stability.

Comment. I agree with these recommendations because controlled drainage of surface water helps to protect landslide and potential landslide areas (Holtz and Schuster, 1996). Surface-water drainage generally is used in combination with subsurface drainage and other remedial measures. However, even with drainage in place, it is conceivable that landslides could result from scenarios of high snow pack, rapid snow melt, and intense spring or early summer rainfall. A comprehensive drainage plan is essential for managing the increased runoff and infiltration that would result from ski area development and snowmaking. Numerical modeling of surface-water flow, infiltration, and ground-water flow is a useful tool for designing adequate drainage measures.

Adequacy of Forest Service Investigation

The Forest Service report is adequate for identifying and making a general ranking of slope stability problems that might arise and problem areas that might be affected by ski area development. It is useful in evaluating the completeness of more detailed slope stability investigations and plans for ski area development. Due to the qualitative nature of the risk assessment it contains, the use of generalized GHU's, and difficulty in reproducing some of the steps used in arriving at the rankings, the Forest Service report is adequate only as an overview of, rather than a detailed guide to, existing conditions, potential landslide problems, and possible mitigation approaches for Snodgrass Mountain.

Proponent's Report

Approach of Proponent's Investigation

The proponent's report (GEO-HAZ Consulting, Inc., 2008) comprises a multidisciplinary approach to assessing the potential impacts of ski area development on erosion and slope stability at Snodgrass Mountain. The report includes interrelated studies of geology, geophysics (shallow seismic exploration), surface water hydrology, ground-water hydrology, ground-water and surface-water interaction, and geotechnical engineering (including analysis of slope stability, ground movement, and measurement of material properties). The study relies on a combination of field data collection and engineering analysis. Subsurface investigation and geotechnical analysis focused mainly on the landslide complexes on the southeast side of Snodgrass Mountain.

Strengths of the Proponent's Investigation

The primary strengths of this approach are the reliance on field measurements and observations to constrain analyses and the use of a wide range of disciplines to define the various inputs needed for slope stability analysis. The approach has resulted in definition of specific areas of concern and specific plans for mitigating the effects of ski area development in those areas. The overall approach is logical and seems generally consistent with engineering practice although there are relatively few, if any, examples of predevelopment geotechnical analyses of ski areas in the open literature. In most cases the report clearly separates data and observations from analyses. Most assumptions and steps in arriving at various conclusions are clearly stated. The data-collection process and presentation of data and analyses are clearly directed towards obtaining the information needed to conduct slope stability analyses of the southeast side of Snodgrass Mountain. The method of stability analysis used (Bishop, 1955), although applicable only to failure along surfaces that are circular in cross section, is widely accepted, especially for preliminary or exploratory stability analyses (Abramson and others, 2002).

Weaknesses, Inconsistencies, and Deficiencies of the Proponent's Investigation

Despite an obvious effort to conduct a comprehensive study, the proponent's investigation suffers from weaknesses in its approach and execution. The primary weaknesses of the approach are (1) heavy reliance on seismic surveys in place of geotechnical boreholes due to difficult access conditions at the site, (2) scope and duration of ground-water investigation, and (3) scope of the geotechnical investigation. Additional weaknesses include inconsistencies and logic errors in some of the hydrologic and geotechnical analyses, lack of analysis to support design of horizontal drains, and inadequate scope of analysis for hydrologic and geotechnical conditions that may affect future slope stability on Snodgrass Mountain.

Geophysics

Because the study area was accessible only by a small, track-mounted drill rig, seismic surveys were used to locate geologic contacts and the water table and to distinguish between bedrock types to depths of 150 ft. This approach was mandated by the need to minimize environmental damage caused by subsurface investigation (chapter 3, GEO-HAZ Consulting, Inc., 2008). Seismic surveys are a valuable addition to subsurface investigations and appropriate at this site. However, too few boreholes were available to constrain the interpretation of seismic data, and the depth of boreholes ranged from 20 to 117 ft., with most less than 90 ft. The seismic surveys indicate an uneven bedrock surface tens of feet below the ground surface. While I am not qualified to comment on the specific methods and techniques used in conducting and interpreting these surveys, I note that geologic boundaries and other information interpreted from weakly constrained seismic surveys have greater uncertainty than interpretations based on abundant borehole data.

Uncertainty in results of the seismic surveys manifests itself in the following ways: (1) mismatch in depth of imaging and wave velocities at the ends of adjoining seismic sections (tomograms) as depicted in chapters 3 and 8 (GEO-HAZ Consulting, Inc., 2008), (2) differences as great as one third in the interpreted depth of landslide shear surfaces based on P-wave and S-wave tomograms, and (3) major differences in the locations of high velocity zones between P-wave and S-wave tomograms, even though some differences might be expected due to the different responses of P-waves and S-waves to ground water. In constructing the cross sections for slope stability analysis, geologic contacts were traced along lines of roughly constant S-wave velocity and the water table (unconfined) was projected along lines of roughly constant P-wave velocity of 5,000 ft/s (chapter 8, GEO-HAZ Consulting, Inc., 2008). Although this is a logical approach, it is subject to error without adequate borehole control. For example, the maximum recorded P-wave velocity, 12,000 fps, is within the observed range for shale and there is sufficient overlap between the wave velocities of different rock types that it is impossible to distinguish lithologies, such as shale versus porphyry, based on seismic velocity alone (Telford and others, 1976). In most instances, depths imaged by the seismic surveys are not adequate to identify presumed sills well enough to make a positive identification for purposes of assigning strength properties for stability analysis or inferring potential pathways for deep ground-water flow.

Geotechnical Measurements

Surface Displacement. In addition to the difficulties described in the report (chapter 4, GEO-HAZ Consulting, Inc., 2008) the primary weakness in the displacement monitoring is the small number of long-term observations available and systematic errors that make measurements from certain dates unusable. Given the limitations of the data, the proponent's interpretation seems logical and reasonable. Evidence for block movement of part of the East slide is strengthened by observations that the fence has been reconstructed two or three times (fig. 2-14, GEO-HAZ Consulting, Inc., 2008). Inclinometer data available at the time the report was written were not sufficient to indicate subsurface movement. Monitoring of surface and subsurface movement, with an adequate number and distribution of points and inclinometers to provide redundancy and reduce ambiguity in the interpretation of future slope deformations, ought to be an important part of future studies as well as the long-term mitigation package for the proposed ski area. Deep inclinometers penetrating bedrock should be installed in some of the critical slide areas as suggested by Cotton, Shires, and Associates, Inc. (2008).

Soil Strength. Measurement of shear-strength parameters (cohesion and angle of internal friction) for each of the geologic units present on the southeast side of Snodgrass Mountain provided essential, but probably inadequate, data for performing limit-equilibrium slope stability analysis. Redundant testing was performed for only a few of the materials, leaving considerable uncertainty about the appropriate values of shear-strength parameters for the remaining materials. Compilation of shear-strength measurements included the unexpected result of higher residual strength of weathered shale than unweathered shale. This difference may or may not be real but cannot be determined satisfactorily from the information provided. In addition to these concerns, the proponent's report provides no information about the range of normal stress used in determining the shear-strength parameters. Soil-strength tests for stability analysis should be conducted over the range of expected normal stresses acting on the slip surface(s) of the landslides being analyzed (Wu, 1996).

Residual strength was correctly used to represent strength of the basal slip surfaces of landslide deposits (section 4.4, GEO-HAZ Consulting, Inc., 2008), but peak strength is probably not relevant to the Mancos Shale. Residual strength is generally considered relevant to reactivation of landslides (Skempton, 1985; Wu, 1996; Abramson and others, 2002; Bromhead, 2004) and is the appropriate measure of shear strength for analyses of potential landslide reactivation at Snodgrass Mountain, including preexisting shear surfaces that might exist within the Mancos Shale bedrock. Peak strength is usually considered relevant to first-time slides in natural normally consolidated clay and intact rock, such as porphyry. The fully softened strength (fig. 4) is relevant to first-time failure of stiff-fissured clays, claystone, and clay shale (Skempton, 1985; Wu, 1996) and would be a more appropriate measure of strength for the Mancos Shale than the peak strength in the analyses where preexisting shear surfaces can be ruled out. Given the fractured nature of much of the Mancos Shale, fully softened strength is more relevant to future failures of the shale than the peak strength.

The proponent adjusted the angle of internal friction of the shale for deep, curved failure surfaces by taking a weighted average of two-thirds the residual strength and one-third the peak strength (section 8.2.4.4, GEO-HAZ Consulting, Inc., 2008). While the shear strength of the Mancos Shale may be anisotropic (greater strength across bedding than parallel to it), the procedure used for adjusting the friction angle of the Mancos Shale is speculative and probably not relevant to preexisting shear surfaces regardless of bedding orientation.

Surface water

I am not sufficiently versed in the surface-water modeling techniques to comment on this section of the report (chapter 5, GEO-HAZ Consulting, Inc., 2008).

Ground water

Piezometer Observations. The ground-water investigation (chapter 6, GEO-HAZ Consulting, Inc., 2008) provides much valuable data; however, its scope and duration are inadequate. The piezometers are scattered among the various landslide deposits and provide a glimpse of ground-water conditions, but no clear picture for any of the separate landslide deposits. With the exception of the East slide, which has four piezometers, most young landslide deposits have one or none. A number of the piezometers used in this study were installed a few months before the report was written. USGS experience monitoring landslides in various geologic environments (Iverson and Major, 1987; Baum and Reid, 1995; Reid and others, 2008) indicates that new piezometers in clay-rich rocks and deposits typically require time lasting from days to months for ground-water pressures to equilibrate with their surroundings (especially in the case of open tube piezometers) and that more than one year of data is required before piezometer response can be interpreted correctly. Further, observations from tens of piezometers are needed to correctly interpret hydrology of large complex landslides.

Ground Water–Surface Water Interaction

Flow Direction. There are some inconsistencies between chapters 6 and 7 of the proponent's report in the interpretations of ground-water observations, especially as they relate to the surface water. In chapter 6, most water bearing intervals are considered to be confined because water levels rose in most piezometers after drilling and installation. A number of piezometers are near stream channels and water levels are higher in the piezometers than in nearby streams. On the basis of these differences in water level, the nearby stream reaches are interpreted as gaining, or in other words, ground-water flow is towards the streams. This is restated at the beginning of chapter 7. However, the interpretation changes later in chapter 7, in an analysis of a medium-term (approximately 5 months) response of water levels during the summer and autumn of 2007. Rising water levels observed in six recently installed (July 2007) piezometers were attributed to cumulative effects of autumn rainfall and losing streams (PZ–5, PZ–6, PZ–12, PZ–11, PZ–13, section 7.2.2.2, GEO-HAZ Consulting, Inc., 2008). Several of these were specifically identified in chapter 6 as associated with gaining streams. It cannot be both ways, and ground-water flow toward the stream (gaining) is the only interpretation consistent with the water-level differences.

Water-Level Rise. Insufficient data are available to determine the cause of water-level rises observed in three piezometers during the autumn of 2007. The observed water-level rises, presumed to be in response to autumn rainfall events might have resulted from direct infiltration as stated in chapter 7. However, hydraulic connection between the streams and the confined water bearing layers has not been clearly established. Rather, the proponent's interpretation of confined water bearing layers implies that there is little or no hydraulic connection between the streams and the layers. Alternately, the gradual rises (PZ–6B, PZ–11, PZ–12, and PZ–13A, fig. 7-4, GEO-HAZ Consulting, Inc., 2008) might result from consolidation of borehole backfill or a deep source of ground water in which pressure increase lags spring melt by several months. Rapid, short-term response (PZ–2) may have resulted from barometric pressure changes associated with the rainfall (Freeze and Cherry, 1979), rather than infiltration as asserted (GEO-HAZ Consulting, Inc., 2008). As noted previously, some, though not all, piezometers installed in clay-rich landslide deposits require many weeks to months to adjust to their surroundings (Baum and Reid, 1995). Autumn 2008 water levels should be recorded before attempting to interpret piezometer responses from the autumn of 2007. Water-level patterns vary from year to year, and reliable interpretation of ground-water behavior in landslides that have low hydraulic conductivity requires continuous records of several annual cycles (Iverson and Major, 1987; Mark Reid, USGS, oral commun., 2008).

Peak Ground-Water Levels. The proponent's assumption that slope destabilizing ground-water levels will always occur during years of maximum precipitation is misleading (section 8.1, GEO-HAZ Consulting, Inc., 2008). For example, the simple steady-state model for ground-water response to infiltration presented in chapter 7 (section 7.2.3.1, GEO-HAZ Consulting Inc., 2008) assumes that water-table rise from increased infiltration of meltwater from artificial snow will be directly proportional to increased runoff of snowmelt (half runs off and half infiltrates). Drainage with annual return to pre-snowmelt water levels, as observed in PZ–15, PZ–16, and SG–3 (fig. 7-4, GEO-HAZ Consulting, Inc., 2008) is implied. However, precipitation during the previous year(s) and the timing, rate, and magnitude of spring snowmelt and intense spring rainfall are also likely factors in determining peak ground-water levels. The record of deep ground-water observations at Snodgrass Mountain is insufficient to rule out the possibility of high ground-water levels and landslides occurring in years of average or above average (but not necessarily extreme) precipitation, particularly after several years of snowmaking. Occurrence of the Gold Link slide on Mount Crested Butte in spring 2001, a year of below average precipitation (89 percent according to table 8.1) illustrates this possibility. Several years of piezometric observations would be required to observe how water levels respond to multiyear precipitation patterns or long-term increases in snow pack (and infiltration), such as would result from snowmaking.

Stability Analysis

Historical Analogy. The stability analysis by historic analogy, section 8.1 of the proponent's report, identifies only five subwatersheds in which landslides might be destabilized by infiltration of meltwater from artificial snow. However, as many as 24 subwatersheds may be vulnerable. Section 8.1 is based on the proponent's assumption that no landslide movement has occurred in historical times and that maximum ground-water levels occurred in 1984, the year of maximum recorded snow pack (143 percent of average) at the Mount Crested Butte SNOTEL site (table 8.1, GEO-HAZ Consulting, Inc., 2008). Given the evidence for block movement of the East slide, the assumption of no landslide movement appears to be incorrect, even though no open fractures are evident along the flanks of the East slide and no major movements have been reported previously. As noted previously, the assumption that maximum ground-water levels occurred in the year of maximum snowpack is undocumented, imprecise, and misleading because rate of melt, spring rainfall, long-term precipitation patterns, and other factors also affect ground-water levels. The identification of five subwatersheds is based on predicted infiltration due to melting of artificial snow and trail clearing, along with average precipitation exceeding 143 percent of normal levels. The argument made in section 8.1 that only these five watersheds might be affected seems to be based on an assumption that net infiltration amounts resulting from melting of above-average snowpack combined with clearing and melting of artificial snow will never exceed infiltration ratios computed for average precipitation combined with clearing and melting of artificial snow (appendix 8.1, GEO-HAZ Consulting, Inc., 2008). However, this contradicts information and model results presented in table 5.5 of the proponent's report (GEO-HAZ Consulting, Inc., 2008), which indicates that melting of artificial snow will increase runoff even in years of above-average snowpack. As noted in the Forest Service report, snowmaking can be expected every year, because snowmaking occurs mainly in the fall before it is known how much snow will accumulate naturally. Consequently, landslides could be destabilized in subwatersheds receiving infiltration increases resulting from clearing and melting of artificial snow where the increases result in infiltration ratios less than 143 percent. For example, there are 24 watersheds predicted to experience infiltration increases of 20 percent (infiltration ratio of 120 percent) or more (appendix 8.1) and various combinations of artificial snow and above-average natural snowpack are likely to push many of these above the 143 percent threshold. These watersheds should be checked for the presence of landslides or unstable slopes.

Limit-Equilibrium Slope Stability Analysis. Cross-section alignment for limit-equilibrium slope stability analysis should follow the main axis of the landslide, parallel to the downslope movement direction. Cross-section alignment is obviously challenging in complex terrain like that on the southeast side of Snodgrass Mountain. Alignment of the east cross section comes close to the ideal, but probably should extend a few hundred feet farther upslope to include the entire head of the landslide. The central and west cross sections seem poorly aligned for performing stability analyses of several of the landslide polygons. In particular, the main axes of polygons 11, 20, 21, and 22 are oblique to the line of cross section (figs. 2-12, 2-13, and plate 1, GEO-HAZ Consulting, Inc., 2008). The results of this misalignment are that (1) the slope angle is flatter in analyzed cross-sections than along the axis of landslide and (2) in most cases the cross section does not extend from the head to the toe of the slide (plate 1 and figs. 8-4, 8-7, 8-8, 8-9, 8-15, 8-16, 8-17, GEO-HAZ Consulting, Inc., 2008). The net effect of the misalignment is that the computed factor of safety will usually be higher than in the true factor of safety.

However, despite flaws, limit-equilibrium slope stability analysis shows that some of the deposits have low factors of safety and are sensitive to disturbance.

Computed factors of safety suggest there may be some heterogeneity that cannot be accounted for with the existing suite of shear strength measurements. For instance, the high factor of safety of landslide polygon 22 (figs. 8-16, 8-17, GEO-HAZ Consulting, Inc., 2008) begs the question of how the landslide occurred in the first place. Even accounting for backward rotation to reach its current position, its current factor of safety is unlikely to be as great as computed (2.42). The high factor of safety can in part be attributed to the misalignment noted in the previous paragraph. Strength of the basal shear surface is probably lower than assumed. Given the evidence that part of the East slide may be moving, the computed factor of safety, 1.11, probably is too high (chapter 4 and fig. 8-22, GEO-HAZ Consulting, Inc., 2008).

The range of failure modes considered in the slope stability analyses is incomplete for some cross sections. For example, the potential for failure of the steep toes of some of the landslide deposits should be analyzed. The aspect ratios (thickness:length) of many of the deposits are consistent with translational movement, rather than rotation (Abramson and others, 2002). Factors of safety for long, thin landslides ought to be checked using another analysis method, rather than the method used, which only permits the analysis of rotational failures. Similarly, the factor of safety computed for landslide polygon 1 (figs. 8-19 and 8-20, GEO-HAZ Consulting, Inc., 2008) ought to be checked using a method of slices that is suited to irregular failure surfaces. Stability analyses assuming rotational failure would also be appropriate for this landslide polygon. The potential for deep failure surfaces at residual strength in the Mancos Shale should be considered in the analyses as suggested by Cotton, Shires, and Associates, Inc. (2008). Stability analyses for complex landslides such as the East slide, which was mapped as consisting of several smaller component landslides of different ages, should also include analysis for reactivation of the entire landslide complex and each of its components, not just the "youngest" ones.

No slope stability analysis was performed for landslide polygons 23 and 42, even though they are young landslides and likely to receive additional infiltration as a result of trail clearing and melting of artificial snow. Other landslide polygons should be analyzed as well, regardless of their perceived age, if they are either on steep slopes, have high water levels, proposed to receive artificial snow, or are otherwise potentially unstable or hazardous. Polygons that should be considered for analysis include 2, 10, 12, 24 and perhaps others along major trails receiving snowmaking in GHU's 6 and 12.

Slab Failures. The analysis for the potential of slab-type failures similar to the Gold Link slide on Mount Crested Butte is weak (section 8.4, GEO-HAZ Consulting, Inc., 2008). Although a slope map is a reasonable first estimate of locations susceptible to shallow failures, a single example is not sufficient to establish that 17° is the minimum slope angle for such failures. The discussion that considers the potential for debris flows to damage infrastructure does not consider the potential for resource damage that could result from sediment entering streams on the southeast side of Snodgrass Mountain (section 8.4.2 and fig. 9-2, GEO-HAZ Consulting, Inc., 2008). As noted previously, salt and metal contamination from exposed Mancos Shale has the potential to seriously damage aquatic and wetland resources.

Future Variations. The hydrologic effects of clearing and the melting of artificial snow are greater in wet years than estimated by the proponent in section 8.5 on "Variations in Future Factors of Safety with Time." The proponent refers to computed runoff values from surface-water modeling and concludes that the increment of water added by development actions is too small to have any effect except in years of extreme precipitation (143 percent of average, 1984; 138 percent, 1995). For example, the proponent's computed increment of water added by development actions ranges from 7.8 percent in wet years to 18 percent in dry years at node A3 (table 5.5, GEO-HAZ Consulting, Inc., 2008). However, those percentages were computed relative to total predevelopment (existing) volume for wet and dry years respectively. Referring to the proponent's table 5.5, the hydrologic effect at node A3 can be correctly computed for comparison with the proponent's threshold (143 percent of average snowpack) as follows: The difference of the "proposed plus snowmaking" volume and the "existing volume" for a wet year divided by the "existing volume" for an average year ((794.33–736.45)/388) is 14.9 percent. This puts any annual snowpack exceeding 128 percent of average combined with additional input resulting from development within reach of the proponent's 143 percent threshold for landslide movement (128%+15%=143%) and magnifies the hydrologic effects of extreme snowpack years (143%+15%=158% of average). Although these effects are localized, there is increased potential for landslide occurrence during extreme snowpack years, and increased frequency with which the threshold may be exceeded. For example, snowpack from 5 of the 24 years of records cited by the proponent (1984, 1986, 1893, 1995, and 1997) when combined with additional water from artificial snow and clearing equal or exceed the amount during the second highest extreme year, 138 percent in 1995. Furthermore, the long-term effect near node A3 may be equivalent to an increased average annual snowpack of 14–15 percent. A complete suite of stability analyses is needed that will include computations for pre- and post-development water levels during extreme snowmelt or precipitation events.

Remedial Measures

The design of remedial measures appears to be primarily conceptual, which makes it difficult to evaluate the effectiveness of the proposed measures (chapter 9, GEO-HAZ Consulting, Inc., 2008). Control of surface runoff and subsurface drainage are useful measures for reducing the effect of increased infiltration resulting from clearing and melting of artificial snow on slope stability. Well designed and implemented surface drainage measures usually improve slope stability (Holtz and Schuster, 1996). Ground-water pressure acting at the basal slip surface(s) of the landslides is the quantity that must be reduced to improve stability. Drains must reduce water pressure at the slip surface to be effective. Artificially applying water (snowmaking) anywhere on a mountainside where slope stability is a concern should be undertaken only where adequate surface and subsurface drainage measures are in place.

Incompleteness of the proposed measures is evidenced by the lack of surface drainage measures to intercept additional runoff from melting of artificial snow on and directly upslope from several young and young-intermediate landslide deposits in GHU's 1A, 3, and 6 (plate 1, GEO-HAZ Consulting, Inc., 2008). Low hydraulic conductivity of the clay-rich deposits of Snodgrass Mountain (10^{-5}–10^{-7} cm/s; table 6-4, GEO-HAZ

Consulting, Inc., 2008) indicates that subsurface drainage measures will have limited effect and may only reduce ground-water pressure in the immediate vicinity of the drains, with little overall improvement in slope stability. Seasonal rise and fall of water levels and ground-water pressures in connection with annual spring snowmelt (fig. 7-4, piezometers PZ–15, PZ–16, SG–3, SG–4, SG–5, GEO-HAZ Consulting, Inc., 2008) indicates that a certain amount of natural drainage exists in those deposits; however, its existence does not guarantee the success of horizontal subsurface drains. In addition to adequate hydraulic conductivity, the effectiveness of horizontal drains also depends on the relationship of the water table (or piezometric level in the case of confined layers) to the basal slip surface of landslides. If the water table is only a short distance above the slip surface, then drainage is unlikely to be effective (Cornforth, 2005). Although the height of the water table above the slip surface is at least half the depth of the landslide in most cross-sections (figs. 8-2, 8-7,8-18, and 8-21, GEO-HAZ Consulting, Inc., 2008), the actual relationship between the water table and the basal slip surface remains undetermined, because their actual locations are known at only a few points.

Main Conclusions of Proponent's Report

1. **Bedrock Geology**. Based on geologic field work, the proponent determined that the transition zone at the base of the laccolith is more complex than indicated by previous mapping (Gaskill and others, 1991). The proponent identified thin sills of Tertiary porphyry on the southeast side of Snodgrass Mountain and indicated that these sills contribute to the occurrence of landslides by conveying ground water into the area. The flow of ground water is facilitated by the gentle folding and southeastward dip of the bedrock (section 2.7, GEO-HAZ Consulting, Inc., 2008).
   Comment. I agree that field evidence presented in the report seems to support this conclusion. However, the report does not appear to contain any analysis of the potential for long-term contributions of melting of artificial snow on the upper Mountain to elevated ground-water levels in the sills or the effect of such elevated water levels on slope stability.

2. **Surficial Deposits**. Exploratory borings showed that unconsolidated surficial deposits, including landslide and glacial deposits, overlie bedrock on the southeast side of the mountain. These deposits lie directly on intact shale below the maximum height of the Pinedale glaciation and on weathered shale above that height (section 2.5.4, GEO-HAZ Consulting, Inc., 2008). The area called the slump block (Baum, 1996) is underlain by a thick sequence of unconsolidated deposits, including till and possibly landslide deposits (section 2.5.3b, GEO-HAZ Consulting, Inc., 2008).
   Comment. These findings are important because they determine many of the inputs for slope stability analysis.

3. **Ground Water**. A saturated zone, 3–23 ft thick, rests on bedrock and zones of perched water occur locally in surficial deposits (section 2.5.4, GEO-HAZ Consulting, Inc., 2008). Ground water is confined in young landslide deposits, and generally unconfined or weakly confined in older landslide deposits. In some piezometers, ground-water levels rose in response to snowmelt in the spring of

2007 and then dropped over several months (section 6.1 and fig. 7-4, GEO-HAZ Consulting, Inc., 2008). Ground-water rise was also observed during the fall 2007 in a few recently installed piezometers (July 2007; section 7.2.2.2, GEO-HAZ Consulting, Inc., 2008).
Comment. These findings illustrate the complexity of the ground-water system in the landslide and surficial deposits on Snodgrass Mountain. Long-term monitoring at many more piezometers will be needed to adequately characterize the effect of snowmelt and rainfall infiltration and development actions on the ground-water system and slope stability.

4. **Surface Water Modeling**. Surface-water runoff is predicted to increase locally in response to melting of artificial snow. However, the depth of flow will increase by only a small amount and increased erosion is unlikely except in the lower part of watershed "A" (fig. 5.1, GEO-HAZ Consulting, Inc., 2008) on the southeast flank of Snodgrass Mountain.
Comment. This conclusion is surprising and should be evaluated carefully, because of potential for increased erosion by concentrating flow in drainage ditches, culverts, and along roads.

5. **Ground Movement**. Long-term survey of monitoring pins and analysis of a survey of fence posts indicates that the upper few feet of surficial deposits on the southeast side of Snodgrass Mountain are creeping downslope (section 4.2, GEO-HAZ Consulting, Inc., 2008). Observed movement patterns are also consistent with a component of deeper landslide movement on part of the East slide. The proponent's report noted that downslope soil creep and landslide block movement should be considered in design of ski area facilities.
Comment. These conclusions are consistent with the data. Evidence for movement of the East slide underscores its sensitivity and potential for reactivation. Long-term monitoring of ground movement at a large network of points on sensitive landslide deposits should be a key component of future development plans.

6. **Threshold Snowpack**. Based on analysis of previous annual precipitation and the absence of any evidence of major landslide movements during a 24-year period ending in 2007, the proponent concluded that annual snowpack exceeding 143 percent of average (by some unknown amount) is required to cause landslides on Snodgrass Mountain.
Comment. This simple threshold is imprecise and probably misleading because rate of melt, spring rainfall, long term precipitation patterns and other factors also affect ground-water levels. Monitoring of surface and subsurface landslide movement and water levels are needed to evaluate this assumption.

7. **Stability Analysis**. Slope stability analysis identified specific landslide areas along the east and central cross section that have low factors of safety (approximately 1.1 or less) and will be further reduced by clearing and melting of artificial snow. These areas can be mitigated by a combination of surface drainage measures in the Chicken Bone area (GHU 6, fig. 3) and subsurface drainage of the landslides (figs. 9-1 and 9-3, GEO-HAZ Consulting, Inc., 2008).
Comment. As noted in the previous section of this report, additional areas may

need to be considered for surface drainage measures, and the effectiveness of subsurface drains has not been demonstrated on Snodgrass Mountain.

8. **Debris Flow Potential**. The proponent considers debris flows or rapid earth flows similar to the 2001 Gold Link landslide on Mt. Crested Butte unlikely (section 8.5.2, GEO-HAZ Consulting, Inc., 2008). Nevertheless, a low debris flow deflection berm was proposed to help protect two lift terminals on the lower part of Snodgrass Mountain (fig. 9-2, GEO-HAZ Consulting, Inc., 2008). *Comment*. Data are insufficient to support this claim. As I have noted elsewhere in this report, historical occurrences under similar conditions on Mt. Crested Butte suggest that such flows are likely post development. No berms were offered to protect wetlands west of the lift terminals nor residential areas from potential debris-flow sources farther downslope and east of the lift terminals (fig. 3).

Adequacy of Proponent's Report

The report contains a more detailed assessment of the engineering geology, hydrology, and slope stability of Snodgrass Mountain than any previous study. By using a morphologically based landslide age classification scheme, analysis of ground movement, and slope stability analyses, the report highlights some particular areas of potential slope instability. The report provides a conceptual or preliminary design for surface and subsurface drainage measures to mitigate landslide hazards on the mountain. Data and analyses contained in the report constitute a valuable contribution to information needed to determine the suitability of Snodgrass Mountain for ski area development. However, the proponent's report has not adequately demonstrated that Snodgrass Mountain can be developed and operated without landslide incident during the expected 50 year project lifecycle. Several important questions remain unanswered and the proponent's report only partially fulfills the need for information upon which to base a decision. These questions concern the adequacy of proposed mitigation, slope stability under extreme climate conditions, stability of specific landslide areas that are not on the lines of cross section, and the potential for shallow landslides and debris flows. These questions are discussed in greater detail in later sections of this report (Suggested Actions and Topics for Further Consideration).

Adequacy of the report depends on the level of risk that is acceptable to the USDA Forest Service. The proponent's report adequately demonstrates that some of the landslide deposits on the southeast side of Snodgrass Mountain have low factors of safety and a high potential for reactivation if disturbed. If the Forest Service has a low tolerance for risk of landslide movement at Snodgrass Mountain (that is, any landslide, even a small one with low to moderate potential for causing personal injury or resource damage, would be unacceptable), then information in the report is sufficient basis for denying a permit for the proposed development. Additionally, if any rapidly moving landslide would be unacceptable, as seems to be indicated in the Forest Service report (p. 69), then the available information, including historical precedent at nearby Mt. Crested Butte (1996, 2001, and 2008 landslides), may be grounds for denying the permit. If the Forest Service has a very high tolerance for risk of landslide movement at Snodgrass Mountain (that is, any landslide except a very large rapidly moving one greater than 10–20 million m_ would be acceptable), then the information in the report is sufficient basis for accepting the proposal. Occurrence of such a large, rapid landslide seems very unlikely because neither this nor any previous report has suggested that a major reactivation of the entire landslide complex on the southeast side Snodgrass Mountain is likely in the absence of major excavation at the toe or major reshaping of the landslide complex (RCE, 1995; Baum, 1996). Such a major reactivation and subsequent potential rapid movement would have great potential for causing multiple injuries or fatalities and major resource damage. Construction workers on the slope and persons present at the foot of the slope or in the valley along the southeast side of Snodgrass Mountain would be exposed to risk of injury from such a landslide. Based on information cited previously (USDA Forest Service, 2006, p.69), the acceptable level of risk may fall between these two extremes and if so, additional studies will be needed.

Areas of Agreement

The Forest Service report and the proponent's report are in agreement in the following areas:

- The southeast side of Snodgrass Mountain is the area of greatest potential for landslide reactivation or movement.
- Gravity-induced slow movement of the upper 60–90 cm (2–3 ft) of soil (soil creep) is widespread on Snodgrass Mountain.
- Active and Young landslide deposits, such as the East slide, should be left undisturbed.
- Slopes on the upper mountain that are underlain by the porphyry bedrock of the laccolith are relatively stable.
- Surface and subsurface drainage would be necessary to mitigate the effects of runoff and infiltration from water added to the slopes by melting of artificial snow.

Comment. These findings indicate with respect to planning that protection of slopes on the lower mountain, particularly the southeast side, requires great care. Avoidance of development on and immediately adjacent to active, historical, and young landslide deposits (or any others that may be shown by future analyses to have a low factor of safety) is necessary to help prevent future movements. Aggressive mitigation measures will be needed to protect such landslides from development actions in their immediate vicinity. The efficacy of surface and subsurface drainage measures for improving slope stability specifically on the southeast side of Snodgrass Mountain must be adequately demonstrated. If drainage proves inadequate other remedial measures, such as mechanical restraints or avoidance, may be necessary. If development is permitted, ski area infrastructure will need to be designed and constructed to withstand the effects of downslope soil creep.

Areas of Disagreement

Debris-Flow Potential. The proponent considers the probability of debris flows or rapid earth flows, similar to the May 2001 Gold Link slide on Mount Crested Butte, to be small (section 8.4.2, GEO-HAZ Consulting, Inc., 2008). The Forest Service report indicates

that there is a moderate to high potential for debris flows or rapid earth flows as a result of disturbance in several of the GHU's (tables 3A, 3B, 3C, 3D, 3E, and 3F, USDA Forest Service, 2006).
Comment. Given their potential for causing injury and resource damage, the difference in opinion about the potential for debris flows or rapid earth flows needs to be addressed by further study of the question.

Magnitude of Drainage Measures. The proponent's drainage plan appears to fall short of the "aggressive surface and subsurface drainage" recommended by the Forest Service. The Forest Service concept for drainage "would entail development of fully integrated, mountain-wide grading, transportation, utility, and drainage plans" (USDA Forest Service, 2006, p. 43). The proponent's plan includes areas of surface and subsurface drainage; however, it is unclear from study of the proponent's map and report (Plate 1, GEO-HAZ Consulting, Inc., 2008) that adequate grading is planned to insure positive surface drainage. As noted previously, several landslide polygons that are crossed by ski trails slated for snowmaking should be analyzed carefully and will probably require subsurface drainage measures, in addition to those landslides where the proponent has already proposed drainage measures.

Missing Information

The following items, listed in order of priority, identify areas on Snodgrass Mountain and topics for which additional information is needed to assess the proposed ski area development. Actions needed to obtain the information summarized here are described in more detail in previous sections of this report.

1. A clear description of standards for acceptable risk with regard to landslide-related resource damage, injuries and fatalities, and offsite impacts.
2. Deep boreholes with inclinometers to determine whether any of the landslides have deep failure surfaces in the Mancos Shale. The inclinometers would need to be monitored for at least 2–3 years; however, monitoring should continue on at least an annual or semi-annual basis throughout the life of the proposed ski area. Monitoring of surface monuments should continue as well.
3. Additional piezometers to determine ground-water pressures at depths of existing and potential landslide slip surfaces in many more locations. Evaluation, by comparison with results of field monitoring at all piezometers for three or more years, of the simple ground-water model used in estimating ground-water pressures for stability analysis. Observational data for the 2007–2008 snow pack and spring time water levels should be extremely valuable for this evaluation. This should be supplemented by ground-water modeling to evaluate the combined effects of increased infiltration and subsurface drainage measures on ground-water levels within the landslides for pre- and post-development normal and extreme precipitation and (or) snowmelt conditions (RCE, 1995; USDA Forest Service, 2006).
4. Additional stability analyses to address the deficiencies identified previously in the section on stability analysis. Analyses are needed for corrected cross-sections and strength parameters, additional trial surfaces and failure modes, additional

landslides, and extreme pre- and post-development ground-water conditions. Additional laboratory tests and additional interpretation of existing test data are required to broaden the database of shear strength measurements. Evaluate the potential for reactivation of large landslides to affect residential areas.

5. Detailed assessment of potential for shallow landslides and debris flows to occur and impact proposed residential areas and surface water/wetlands. Carefully review the need for remedial measures, including berms or other mechanical restraints to protect these areas.
6. Demonstration, through modeling and field experiments, that subsurface drains can be used effectively to reduce ground-water pressures sufficiently to increase the factor of safety of landslide deposits on Snodgrass Mountain. Such experiments would require additional piezometers to monitor the zone of influence of trial drainage arrays. Depending on results, improved design of drainage and perhaps other remedial works will be needed.
7. Field work and analysis needed to demonstrate that construction of the ski trail on the northwest side of Snodgrass Mountain, adjacent to the active landslide (in GHU 10B) will not cause landsliding to spread to the north, into an area which is equally steep and of similar composition to the active landslide area. Existing data may not be adequate to address this question.
8. Field work and analysis needed to demonstrate that clearing and construction of trails, lifts, and other infrastructure in GHU 10A and operations in the southwest part of GHU 12 will not destabilize slopes.
9. Field checking to verify the absence of landslides on the East Facet (GHU 7), and the absence of landslide features in the southwestern part of GHU 12 (the steeply sloping area between Snodgrass Road and the northeastern border of GHU's 3, 5A, and 6; see fig. 2).

Topics for Further Consideration

Future Landslides. Even with mitigation and due care, a small but definite probability of one or more landslides (of undetermined size or magnitude) occurring during the life of the project exists due to unforeseen conditions and other uncertainties. Potential for human error, mechanical failure or breakdown of mitigation measures, geologic uncertainties, extreme weather, and other natural processes contribute to this probability. Occurrence of the Gold Link slide on Mount Crested Butte in May of 2001, a year of below-average precipitation, highlights the potential for unexpected occurrences. Existing landslide deposits on Snodgrass Mountain along with historical landslides and debris flows that have occurred on nearby Mount Crested Butte (1996, 2001, and 2008) are guides to the range of sizes and types of landslides that are most likely to occur. Although proving that a future landslide was caused by ski area development or operations might be difficult, demonstrating that any future landslide within or adjacent to the permit area was completely unrelated to ski area operations or development would be very difficult.

Monitoring. Continuous monitoring of slope stability at Snodgrass Mountain will be needed if the Forest Service authorizes development of skiing facilities. Long-term monitoring of piezometers and landslide movement (inclinometers and surface displacements) at many locations will be necessary for several purposes including (1) checking assumptions about the proponent's simple ground-water model or any subsequent models, (2) annual and longer-term (multiyear) responses to precipitation patterns, (3) clarifying the interaction between ground water and surface water, (4) monitoring changes in slope stability, and (5) monitoring performance of drains. Water-level (ground-water pressure) reductions in landslides or potential landslide areas are more accurate indicators of drain performance than the volume of water discharging from the drains. Enforcement of the long-term monitoring requirement would need to be an integral part of any permit granted for development of ski facilities on Snodgrass Mountain. With monitoring would come a requirement for regular reporting to the Forest Service on the status of slope stability, ground-water pressures, and ground deformation. In the event of persistently rising water levels or evidence of landslide reactivation it may become necessary to suspend ski area operations, particularly snowmaking, and implement additional remedial measures.

Long-term Maintenance. Surface and subsurface drainage systems will require routine maintenance throughout the life of the project to ensure continued operation at acceptable levels of performance (Holtz and Schuster, 1996).

Quantifying Uncertainty. Continued investigation will reduce but never totally eliminate uncertainty about the potential for future landslide activity on Snodgrass Mountain. One approach to dealing with uncertainty is to make what are believed to be conservative assumptions that could result in low estimates of the factor of safety. This approach was used by the proponent and has historical precedence in engineering practice; however, this approach leaves open the question of sensitivity of the analysis to those assumptions. Although preliminary stability analyses were done to check the sensitivity to certain parameters and assumptions, data were insufficient to generate probability density functions (section 8.2 and appendix 8.2, GEO-HAZ Consulting, Inc., 2008) and estimates of the degree of conservatism in the computed factors of safety are purely speculative. A more thorough, though somewhat more costly, approach is to compute the probability distribution for the factor of safety (Abramson and others, 2002; Nadim and others, 2005). Such a computation requires more data, but makes it possible to determine the degree of certainty that the factor of safety is greater than one. Probabilistic analyses are becoming more widely used in engineering practice.

Conclusions

The two reports (USDA Forest Service, 2006; GEO-HAZ Consulting, Inc., 2008) contribute substantially to what is known about the geology and slope stability of Snodgrass Mountain. Both reports demonstrate that the potential exists for reactivation of certain landslides. Depending on the level of risk that is acceptable to the USDA Forest Service, information in the reports may or may not be adequate for making a decision. If USDA Forest Service thresholds for unacceptable outcomes with regard to life safety and resource damage are low (small landslide with minor chance of injury or moderate chance of resource damage) then the information constitutes an adequate basis for denying the permit. If the thresholds are higher, additional studies to reduce uncertainty in the factor of safety calculations, assess the potential for debris flows, design comprehensive surface drainage measures, and demonstrate the effectiveness of subsurface drainage measures will be necessary for decision making. While I agree that surface and subsurface drainage is the best option for improving slope stability at the site, the proposed design appears to be inadequate and more drainage measures may be needed. Engineering calculations and field tests to demonstrate the effectiveness of the proposed subsurface drainage in the clay-rich surficial deposits and weathered shale present on Snodgrass Mountain are lacking. Additional borehole, shear strength, inclinometer, and piezometer data are needed along with more and improved slope stability analyses to demonstrate the effects of melting of artificial snow and drainage measures on future slope stability.

Acknowledgment

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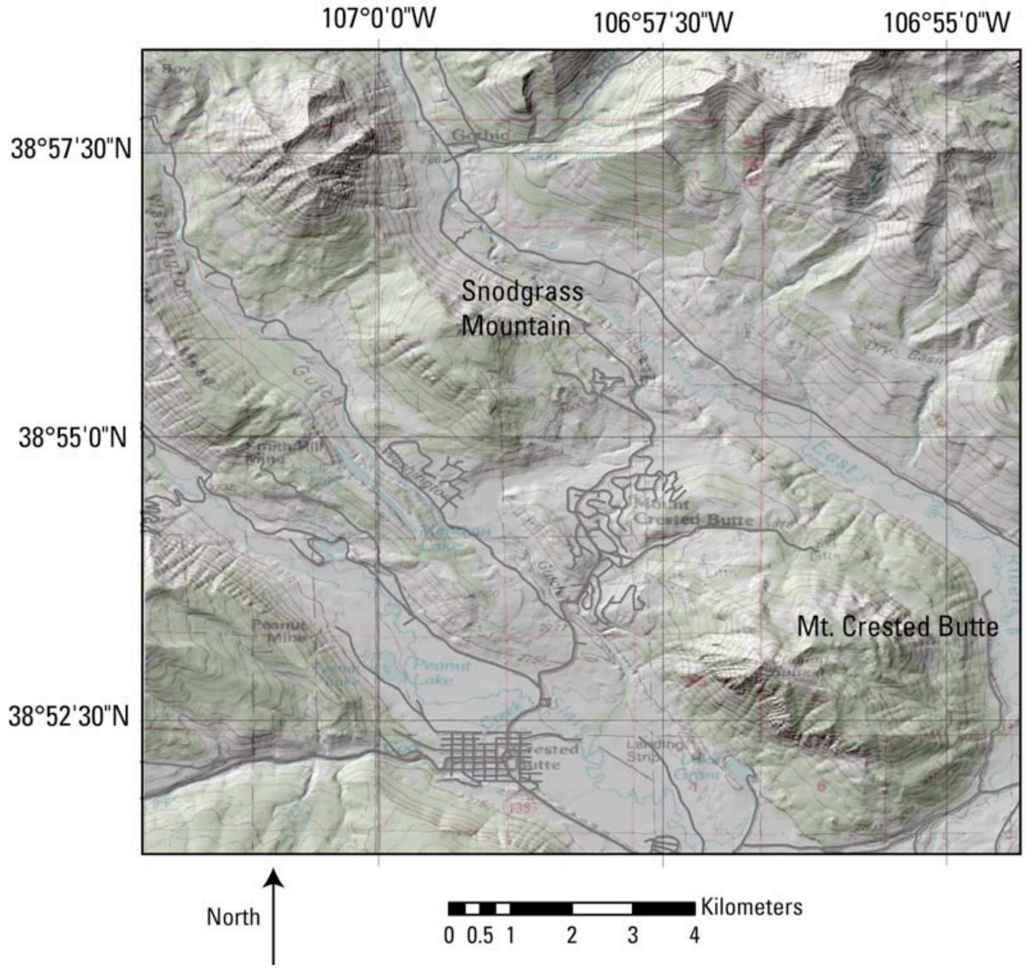

Figure 1. Map showing the location of Snodgrass Mountain, Gunnison County, Colorado.

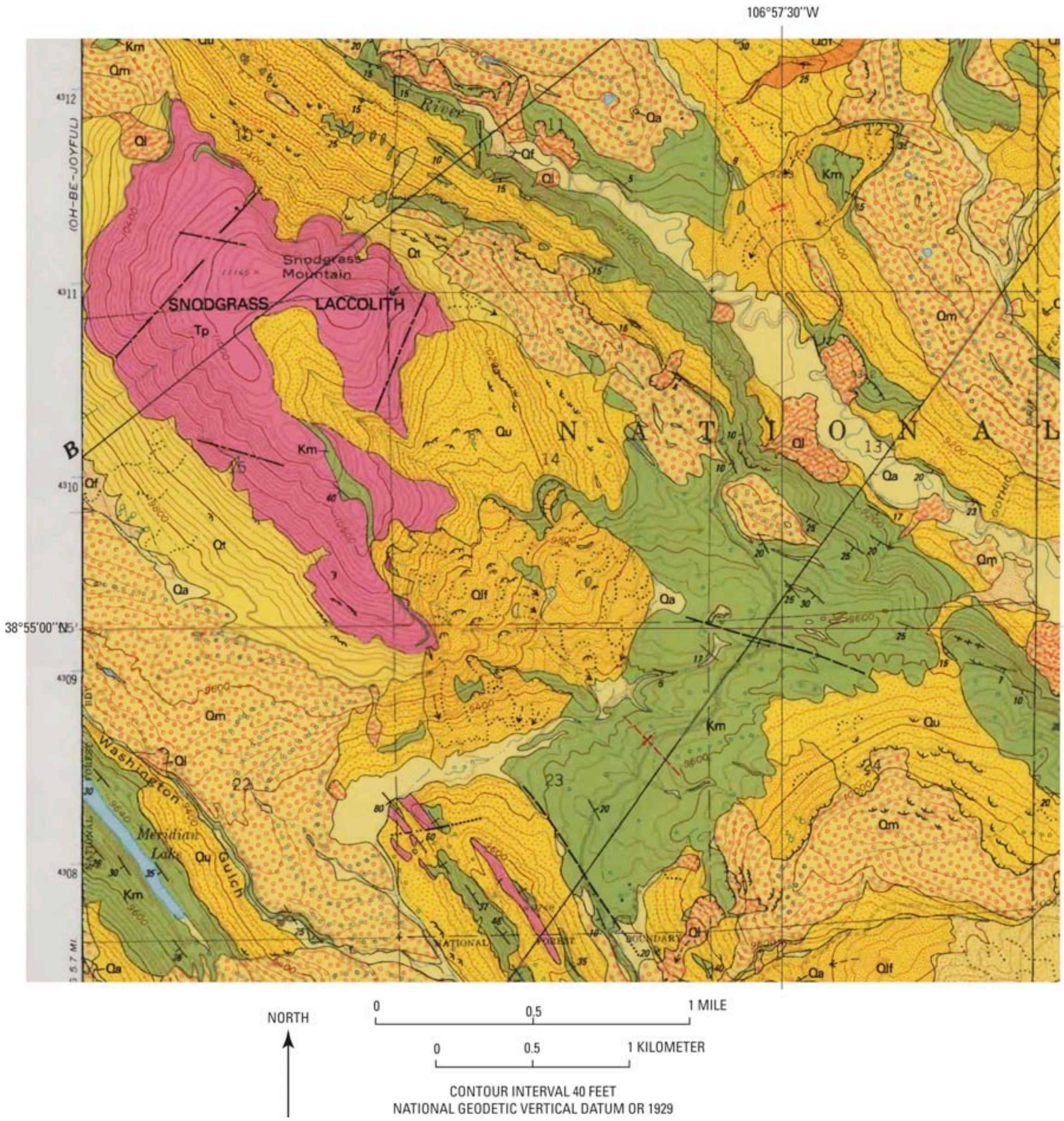

Figure 2. Geologic map of part of Snodgrass Mountain and Mount Crested Butte (Gaskill and others, 1991). Qa, alluvial deposits; Qf, alluvial fan and debris-flow deposits; Qdf, debris-flow deposits; Qt, talus; Ql, landslide deposits, undifferentiated; Qlf, landslide, slump, debris-flow, and earth-flow complexes; Qm, moraine deposits, undifferentiated; Qu, undifferentiated surficial deposits (mostly colluvial slope wash); Tp, quartz monzonite porphyry and granodiorite porphyry; Km, Mancos Shale.

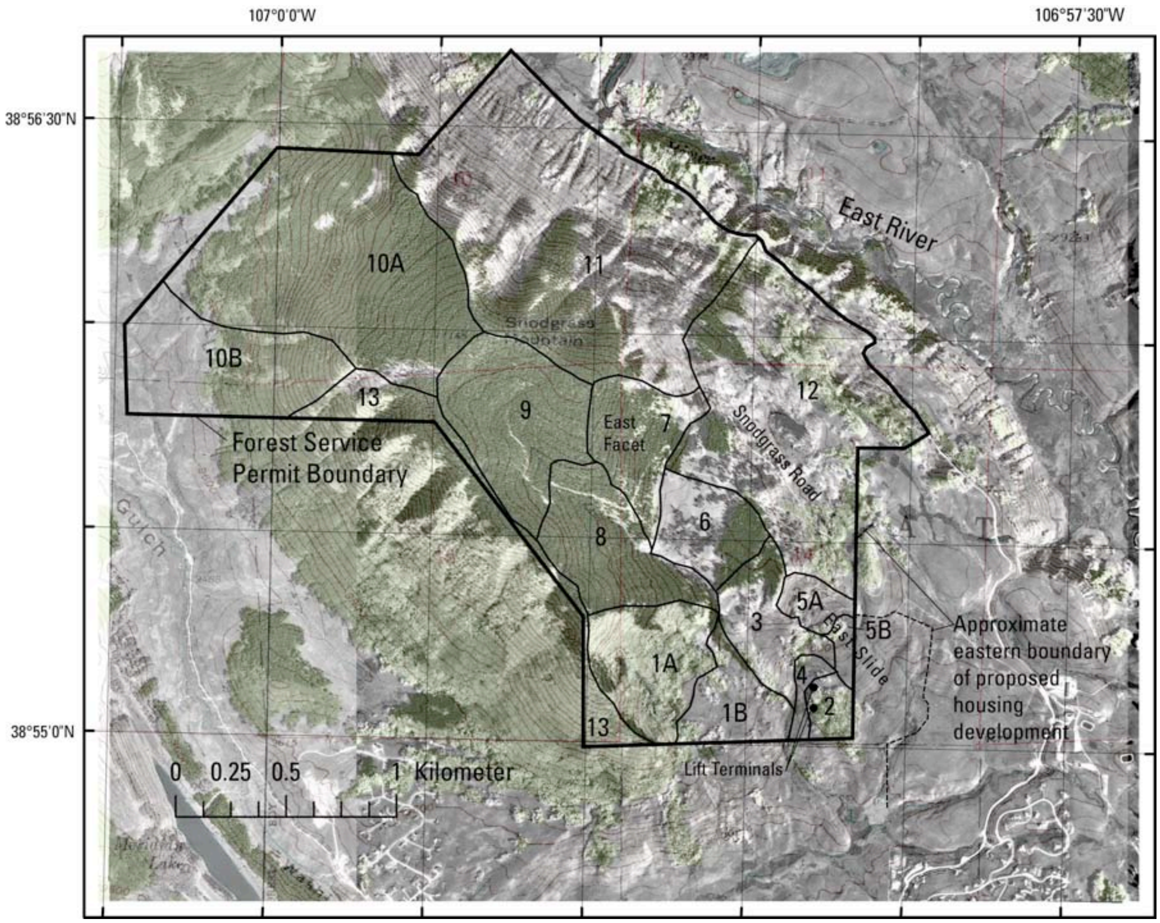

Figure 3. Geologic hazards units (GHU's) designated by the USDA Forest Service (2006) on Snodgrass Mountain. Eastern limit of proposed residential development interpreted from an unpublished site map provided by Crested Butte Mountain Resort, ("Crested Butte Mountain Resort Existing and Future Projects" prepared by Schmueser Gordon Meyer Engineers and Surveyors, dated 12/4/2006). All boundaries shown are approximate; refer to original documents for precise boundaries. Base by USGS, Gothic and Oh Be Joyful 7-1/2 minute quadrangles.

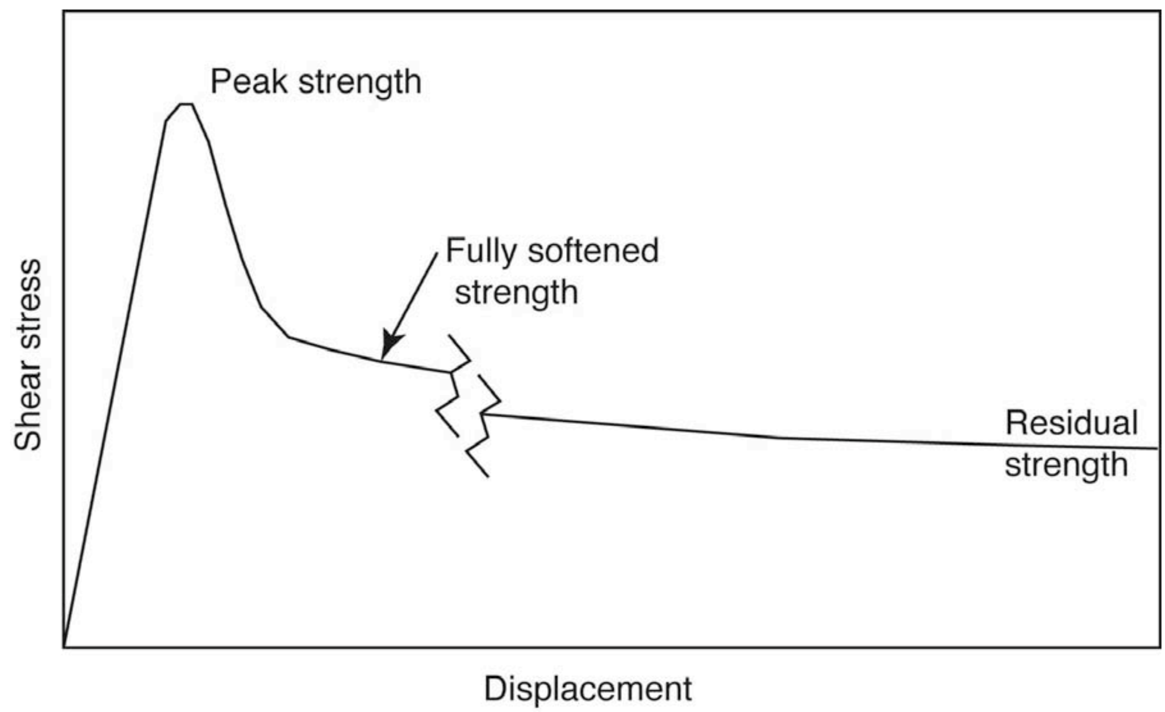

Figure 4. Diagram illustrating shear strength as a function of displacement for fissured clays, claystones, and clay shales (simplified from Wu, 1996). Shear strength varies with displacement, soil porosity, and normal stress. Soft rocks, such as shale, as well as dense and cemented clay-rich soils, display a peak strength that is developed within the first few millimeters of displacement. Upon further shearing, the soil weakens toward the so-called fully softened strength and then after tens or hundreds of millimeters of displacement gradually reduces to the residual strength.