ROCKFALL HAZARD AND RISK STUDY
TOWN OF TELLURIDE
AND
HIGHWAY 145 SPURS

Prepared for:

Town of Telluride

Prepared by:

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In Association with
Wilbur Engineering, Inc.
Durango, Colorado

February 20, 2009

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February 20, 2009

Karen Guglielmone
Public Works Project Manager
Town of Telluride
P.O. Box 397
Telluride, CO 81435

RE: Town of Telluride Rockfall Hazard and Risk Study

Dear Ms. Guiglielmone:

Please find attached the Telluride Rockfall Hazard and Risk Study. This report fulfills the objectives outlined in our Service Agreement.

We appreciate the opportunity to be involved in this important project. Please contact Chris Wilbur or me if you have any questions.

Sincerely,

Arthur I. Mears, P.E.

1. Introduction

The natural cliffs and steep slopes above the town of Telluride generate rockfall events that have reached the town limits and the Highway 145 east and west spurs. Land development is taking place in steeper parts of the platted town where exposure to rockfall is often higher than existing developed areas. Existing areas of town are also exposed. The town plans to improve about 4000 feet of the West Spur of Highway 145 and expand the stage at Town Park. Both public safety and protection of private and public assets will benefit from a better understanding of the rockfall risk and proactive management of that risk, where appropriate.

Although the town has a Geologic Hazard Map that includes an area mapped as "Rock Fall Hazard Moderate to High," the town recognizes the potential to improve upon this map. This study updates Telluride's rockfall hazard map and provides a basis for improved rockfall risk management. We have applied updated knowledge, study of the history of rockfall, mapping tools and methods of rockfall analysis to create a new rockfall hazard map of the existing town and quantify the rockfall risk to the East and West Highway 145 Spurs.

2. Objectives and Limitations

This rockfall hazard and risk study has the following **objectives**:

1. Review existing information, including reports, geologic and topographic maps, aerial photos, and historic records.
2. Complete a field study of rockfall potential in the areas affecting current town boundaries and Colorado Avenue between Society Turn and the Idarado Mill Site.
3. Prepare a Rockfall Hazard Map and Report using the detailed 2008 aerial topographic maps provided by the town. The Rockfall Hazard Map is intended for Land Use Planning Purposes not site-specific mitigation.
4. Prepare a Rockfall Risk Rating for Colorado Avenue consisting of a linear map.
5. Describe Rockfall Hazards in relation to Land Use Planning, transportation, risk management and priorities and provide general recommendations.

This rockfall hazard and risk study also has the following **limitations**, which must be understood by all those relying on the results and conclusions presented herein:

1. The scope of work does not include any mitigation design parameters for rockfall or evaluation of geologic hazards other than rockfall.
2. The scope does not include evaluation of manmade cut slopes or retaining walls.
3. The natural processes that cause rockfall events are not predictable; furthermore individual rockfall events might be either dependent or independent on previous events. As a result, the degree of hazard including assessment of frequency and return period cannot be determined precisely, and it will probably change over time.
4. The maps and hazard boundaries presented are based on the methods described herein and our best estimates and judgment of the hazard levels.
5. It is neither possible nor practical to detect all potential rockfall hazards by any techniques currently in use in rock engineering.

3. Geologic Setting

The rockfall map area is in the glaciated part of the upper San Miguel River valley. The maximum extent of the last glaciation was near the top of Keystone Hill where the terminal moraine is located. Glacial erosion left steep exposures of horizontal to gently north dipping bedded sedimentary formations. In some areas, such as around Mill Creek, Cornet Creek and much of the ski slopes, there is a deposit of glacial till covering the sedimentary rock. This veneer ranges in thickness from a few feet to more than 100 feet. The lower reaches of most slopes are covered with post-glacial colluvial deposits derived from erosion of soil and rock slopes directly above. The valley floor is covered with alluvial (river) and lacustrine (lake) deposits. Figure 1 shows a geologic map of the study area. In vertically ascending order, the following rock units are exposed in the valley[1]:

Cutler Formation is a Permian-aged red sandstone, siltstone and mudstone that generally form slopes and is not a major source of rockfall.

Dolores Formation is a Triassic-aged red to tan sandstone, siltstone and mudstone. This unit is more readily eroded than the overlying Entrada Sandstone, resulting in cantilevered blocks and slabs of rock. This unit, along with the Cutler formation typically forms a relatively uniform slope of 25° to 35° with generally smaller blocks than the overlying Entrada Sandstone.

Entrada Sandstone is a Jurassic-aged cross-bedded fine-grained sandstone that forms bold tan to grey cliff bands 30 to 60 feet thick. This unit is a primary source of rockfall above the town of Telluride. In the project area, this unit has two dominant set of vertical joints oriented about N35E and N65W degrees, with spacing between the joint planes ranging from one to ten feet. The discontinuities, including bedding within and between the units, form rectangular blocks and slabs ranging from about 1 or 2 feet in size up to about 8 to 10 feet, although blocks about 4 to 5 feet are more common. Individual blocks derived from the Entrada therefore may range from roughly 1 ft^3 to as much as 600 ft^3 (approximately 150 lbs to 50 tons). The 4 to 5 foot boulders typically weight about 5 tons.

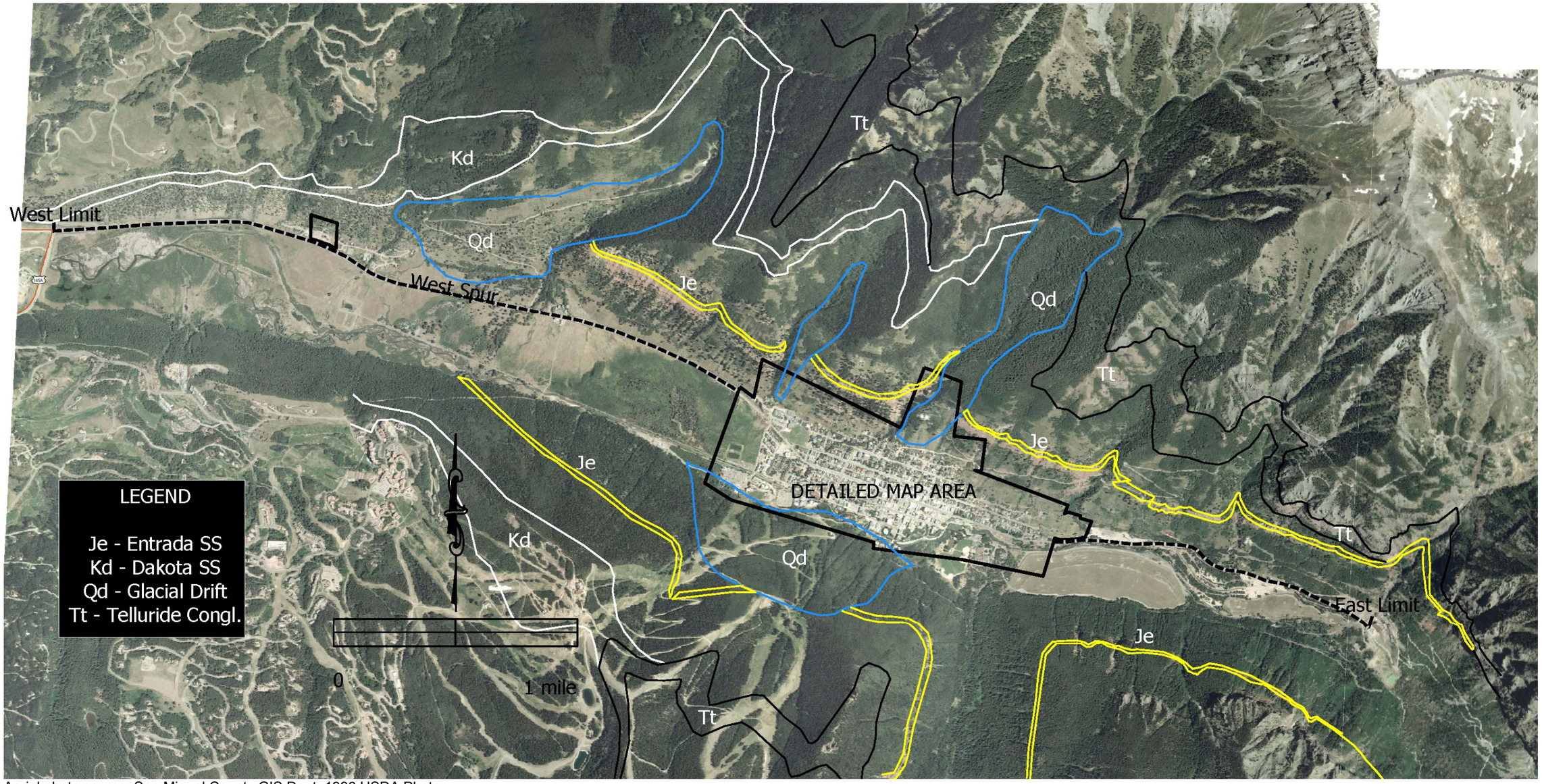
Wanakah Formation is a Jurassic-aged interbedded mudstone, shale and siltstone with thin limestone beds. The Wanakah generally forms slopes However, its limestone beds are a rockfall source at the heads of minor drainages.

Morrison Formation is a Jurassic-aged mudstone with interbedded sandstone and lenses of sandstone near the base. The Morrison is less resistant to erosion than the overlying Dakota and usually forms slopes.

Dakota Sandstone Cretaceous gray to yellow quartzitic sandstone and conglomeratic sandstone with some carbonaceous shale. The Dakota Sandstone forms the cliff band that gradually climbs above the valley floor starting near Society Turn. It is a rockfall source for the West Spur between Society Turn and Mill Creek.

Telluride Conglomerate is a Tertiary-aged grey to red-brown conglomerate with some sandstone, siltstone and shale. This unit along with younger volcanic rocks is a rockfall source at the east part of the study area near Pandora.

[1] (after Burbank and Luedke, 1966, Ref. 1).



Aerial photo source: San Miguel County GIS Dept. 1996 USDA Photo

Figure 1 –Rockfall Study Area

Figure 2 - Primary Rockfall Sources above Town

4. Previous Rockfall Studies

Figure 3 shows the locations of previous rockfall studies. These studies are listed by number in Section 11. We reviewed these studies and considered the data and findings of each. The Groenveld study (Ref. 1) for the east Telluride Addition used tree scars to estimate rockfall frequency. It also described a significant historic rockfall event on Willow Street in the 1960s. The tree scars analyzed in this study provide a good indicator of the frequency of rockfall in the areas where they were measured.

5. Historic Rockfall Events

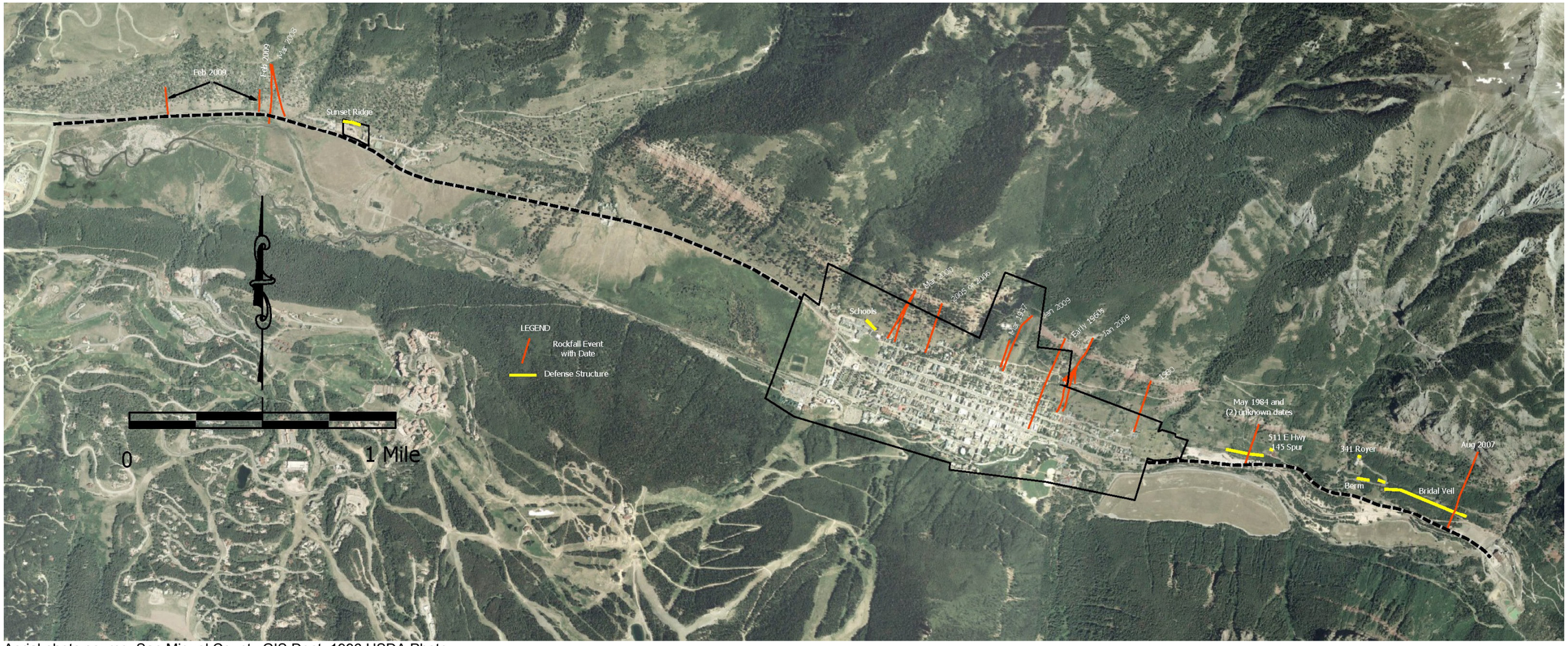
Figure 4 shows the approximate locations of historic rockfall events reaching the East and West Spurs, and also those impacting structures within the town limits. These events have been documented and confirmed by more than one source. Many other rockfall events have probably occurred without being documented. Interviews with long-time Telluride residents indicate that many rocks in the 1 to 2 foot size range have reached town. Larger rocks have reached developed areas of town less frequently. Since most rocks that reach town are removed, historic accounts are often the only source of information about these rockfall events.

Figure 3 - Previous Rockfall Study Locations

March 1937
The Telluride Times reported a “10-Ton” rock damaging a house after it came down a hillside on the north side of town. No address was given, but the owner and tenant’s names were reported as Herbert Lanes and L.L. Pulliam, respectively. Bill Mahoney stated that this house was a white house immediately east of the Historical Museum. He said that the boulder was on the surface of a steep slope and did not originate in a cliff band.

1960s(?) Liberty Bell Event
Several long-time residents described a rockfall event at a Liberty Bell company house in which the rock went through the wall past a person sitting on the couch without causing injury.

Early 1960s
The Groenveld Rockfall Study (Ref. 1) reported that in the early 1960s, a rock the size of a compact car rolled down Willow St. to near Colorado Ave. This rockfall event was reported by Erben Hancock, who lived on Willow St. Other long-time residents confirmed this event.



Aerial photo source: San Miguel County GIS Dept. 1996 USDA Photo

Figure 4 –Historic Rockfall Events and Defense Structures

Summer/Fall(?) 1980
An 18 to 24-inch rock originating above the Tomboy Road went through the east wall of 957 Roadhawg Circle. The occupants were inside the house, but not injured. The rock went through the wall below a window and damaged a piano.

May 1984
An 18 to 24-inch rock went through the roof of a trailer and out the window at the Liberty Bell Mill Site. The occupants, Gary Broderick and his family, were on vacation. Mr. Broderick recalled a different event where a larger rock (about 6-ft.) landed on a pickup truck at Liberty Bell totaling it.

Early 1990s
A 3-foot rock hit a house at the top of Redcliff in the springtime, according to Gary Broderick, who removed the rock.

March 2000
The rockfall of March 3, 2000 started in the Entrada Sandstone outcrop and broke into at least three pieces as it descended the slope. One rock impacted and damaged a house at 715 W. Galena. Another rock crashed through the roof of the school maintenance shop. A third rock damage a parked vehicle. The rock paths were clearly visible in the fresh snow. Large bounce heights exceeding 15 feet (measured vertically) on the steep slope were confirmed by the spacing of impact scars 70-to-100 feet apart observed in the field. (See Figure 5 and Figure 6.)

Figure 5 – March 2000 Rockfall Tracks and Impact at 715 West Galena

Figure 6 – School Maintenance Building Rockfall in March 2000

2005(?)
Town staff reported that a “fridge-sized” rock impacted a shed at 507 West Galena Ave.

August 2007
A large (8-ft.) rock damaged a rockfall fence above Bridal Veil Lane at the Idarado Legacy Subdivision (Figure 7).

Figure 7 - August 2007 Rockfall at Idarado Legacy
(Geobrugg Photo)

March 2008
Town staff described a rockfall event where one rock about 2’ x 2’ x 3’ impacted and crossed the West Spur leaving a dent about 4-inches deep in the pavement of the west bound lane. Another similar sized rock stopped short of the roadway.

January 3, 2009

Following a well above average snowfall in December, roughly 100 cubic yards of rock detached from lower 20 feet of a 70-foot cliff band in Falcon Gulch (between Alder and Maple Streets). Most of the rock material stopped within 150 feet of the base of the cliff. At least a dozen rocks stopped above the Tomboy Road and nine rocks reached Tomboy Road with two of them continuing to properties on the uphill side of Pandora St. traveling about 900 vertical feet. One rock estimated to weigh between 8 and 10 tons impacted and damaged a house under construction at 417 Pandora Street (Figure 8).

The ground was snow-covered at the time and the tracks and impact divots were visible. Measurements of bounce distances along the slope for the two farthest traveled rocks were typically about 30 feet. There was some topographic control of the trajectories, but neither rock ended at the bottom of a gully. Town staff also reported an undocumented single rockfall event in the same area that reached Tomboy Road.

Figure 8 - Rock Inside 417 Pandora St.

Figure 9- Paths of 1-3-2009 Rockfalls

January 23, 2009

Following a week of unseasonably warm weather, several rocks reached Tomboy Road and one impacted a house at 106 Tomboy road. The Town Marshall reported “some damage to the railing and various parts of the house. “ The source is uncertain, but the rock color, texture, and blocky shape were similar to Entrada or Wanaka sources. Two large rocks rolled and bounced past the house. The largest rock measured 4’ x 5½’ x 5’. Several smaller rocks did not leave obvious tracks in the snow. Bounce heights and distances were measured by town staff based on damage to aspen trees and divots in the snow. Aspens were damaged between 3 and 10 feet above the ground near the Jed Wiebe trail crossing. Bounce divots were 30 to 35 feet apart measured along the slope, including the last bounce before impacting the house.

Figure 10 - January 23, 2009 Rockfall Runout
(Town Marshall McReynolds Photos)

February 3, 2009
Two rocks with nominal size of 2-feet reached the West Spur about ¼ mile west of the Eider Creek Condos early in the morning or late the previous night. Much elk activity was noted in the source area. No resources were damaged.

6. Analysis and Mapping Methods

Rockfall Processes

Rockfall processes affecting Telluride result primarily from mechanical weathering in response to slopes over-steepened by glacial erosion. Water seepage and freeze-thaw cycles along with differential erosion contribute to movement and loss of support of more durable blocks defined by natural discontinuities in exposed sedimentary formations. Erosion rates are likely unchanged over a time scale of a few hundred years. However, rockfall events tend to be episodic in response to weather and/or changes in stress conditions including loss of lateral and underlying support.

The dynamics of rockfall motion is complex and depends upon physical parameters that have a distributed range of properties. Important properties include slope height and profile, rock size, shape and durability, and slope roughness, hardness/resilience and vegetation. Human structures, such as roads and buildings, can also affect rockfall dynamics. Rockfall runout distances also vary widely, but exhibit a distribution specific to site conditions. In general, larger, more equidimensional rocks travel farther and have greater energy. Softer and rougher slopes tend to decrease, runout distance, velocity and energy. Bounding height is important for mitigation design, and is mainly a function of rock shape, velocity and terrain roughness and resilience. Observations and modeling indicate that velocity bounding heights decease substantially near the end of the runout.

General Methods

This study utilized a variety of methods to characterize and quantify rockfall hazard and risk. We reviewed available previous rockfall studies. We also reviewed the published geologic

literature. We researched historic rockfall events and interviewed long-time residents and town staff about undocumented or partially documented rockfall events.

We made field observations in the rockfall source areas, tracks and runout areas. Physical properties of rockfall source areas were estimated including rock strength/quality bed thickness, joint spacing and orientation, and degree of undercutting. We assessed the relative susceptibility of outcrops to rockfall initiation. Based on field observations and topography, we identified potential and likely travel paths. Runout distances for representative sources and slope conditions were determined by historic runout distances and evidence of previous events. In developed areas where evidence has been removed, we applied calibrated parameters to simulate rockfall based on areas where rockfall evidence exists.

We assumed that historic rockfall events, whether recorded or indicated by geomorphic evidence, represent the most likely runout distances for future rockfall events. We used these distances and rock sizes and shapes to model rockfall dynamics using the Colorado Rockfall Simulation Program (CRSP). This public domain computer model provides a statistical distribution of rockfall energies, bounce heights and runout distances for a specified profile, ground condition and rock characteristics. The program accounts for both rotational and translational energy. It allows for plastic yielding and variable surface roughness. We also used aerial photographs of various dates to characterize both rockfall source areas, tracks and runout zones.

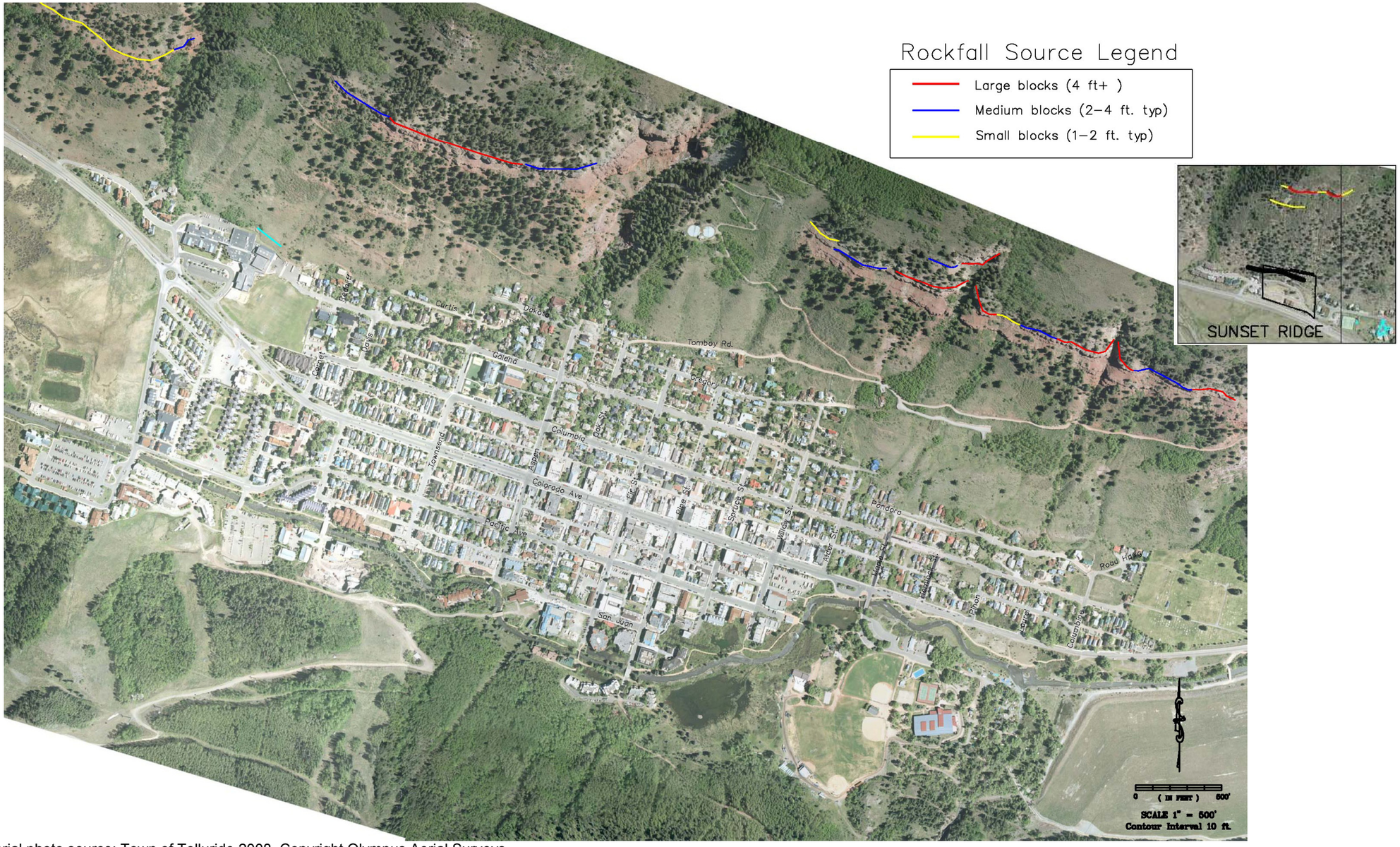
The information described above was combined using Geographic Information System (GIS) software. GIS organizes and allows selective display of various data layers and attributes.

Source Area Characteristics

Figure 12 shows a general division of source areas based primarily on size of potential rockfall blocks. The larger blocks are more likely to form equi-dimensional (quasi-spherical) blocks and be less affected by vegetation in their paths. Thus, larger blocks are expected to have a greater runout distance, larger bounce heights, velocities and energies along their paths.

(a) (b)

Figure 11 - Source above (a) Tomboy (b) Butcher Cr.



Aerial photo source: Town of Telluride 2008, Copyright Olympus Aerial Surveys

Figure 12 - Rockfall Source Areas

Figure 13 - Source above Sunset Ridge

Figure 14 - Source above East Telluride

Figure 15 - Source above West Spur Hwy 145

Hazard and Risk Boundaries

The degree of hazard[2] for any location depends on two factors: (1) the likelihood of a rockfall impact and, (2) the magnitude of the impact. The degree of risk[3] depends on hazard and exposure, and the severity of the potential harm. If all other factors are equal - especially the exposures and the people and property subject to them, then the risk is proportional to the hazard.

The relationship between frequency and magnitude for rockfall is complex and depends on several factors: rock size, number of rocks that reach the point of interest, velocity and energy. The distance traveled and velocity depend on rock shape, size and slope steepness and roughness. In addition, obstacles such as trees and houses can slow or stop rockfalls. We applied the methods described above to determine two zones of rockfall hazard affecting lands within the town limits:

1. The lower boundary (blue line on map) is the approximate rockfall runout limit for 90 percent of rockfall events that are expected to occur within a period of 100 years. The small number of rockfall events that exceed this limit will generally have energy levels of less than 100 kJ (about 40 ft-tons).
2. The upper elevation hazard boundary (red line on map) represents areas that are expected to experience rockfall events with average frequency of 30 years or less and/or where the median energy of the rockfall events is expected to be 500 kJ (200 ft-tons) or more.

These hazard boundaries are approximate and based on limited information and our best judgment. They are intended to give the town and its residents a basis for making informed decisions about managing rockfall risk. *They are not intended and cannot necessarily be used for site-specific design.*

Rockfall Hazard Rating System for Highway 145 Spurs

Rockfall risk along the Highway 145 East and West Spurs owned and maintained by the Town of Telluride was evaluated using two methods. We applied a Rockfall Hazard Rating System designed for artificial roadcuts to arrive at relative risk ratings for various segments of road. We also calculated the probability of death for one vehicle occupant based on estimates of rockfall frequency, size and traffic speed and volume.

Colorado Department of Transportation's (CDOT's) rockfall hazard rating system (RHRS), first published in 1994, identifies and rates cut slopes throughout the state using a combination of slope measurements, traffic data and geology. The RHRS allows CDOT to compare and prioritize rockfall mitigation projects using an objective, rational, defensible method. While this relative risk assessment tool was developed to evaluate cut slopes of heights less than 200 feet high many of the criteria also apply to natural slopes subject to rockfall.

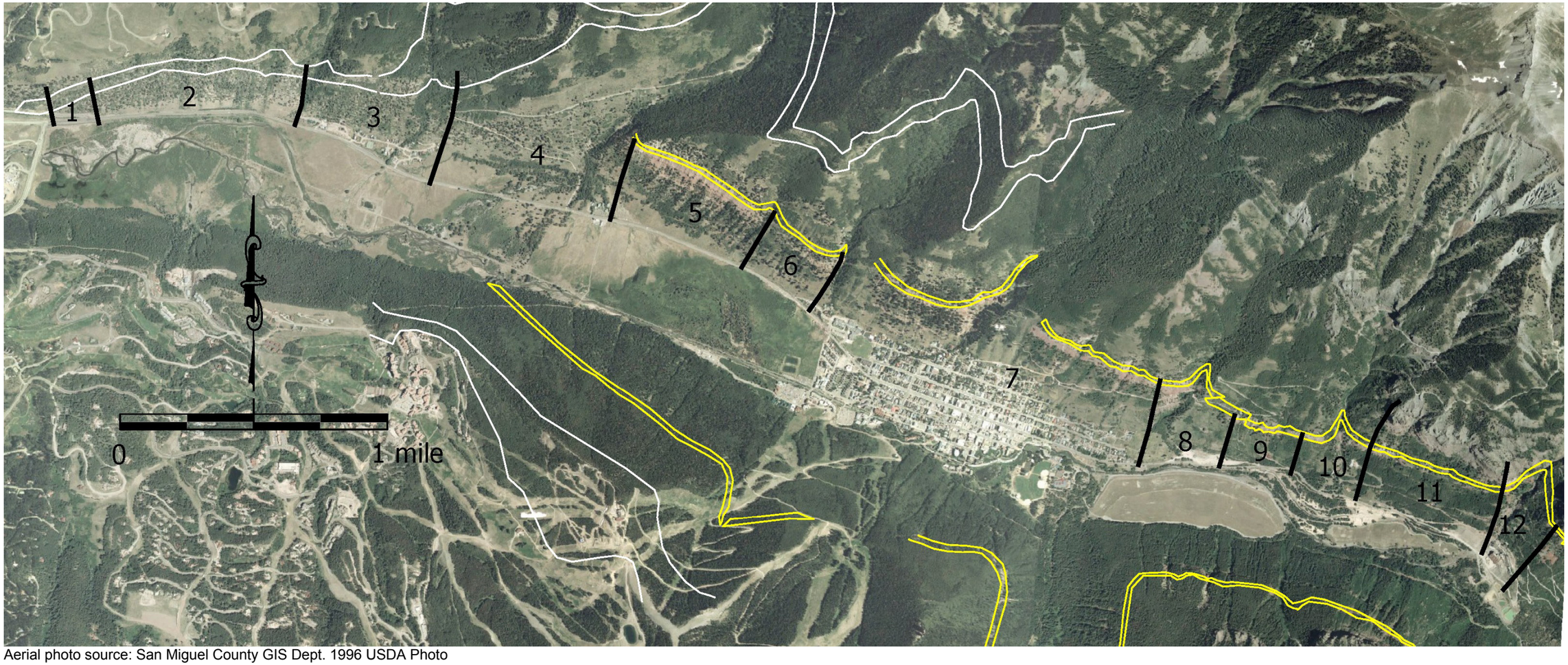
The most recent RHRS ratings from CDOT are from 2003. Scores ranged from a high of 684 on I-70 near Georgetown to a low of 102 (on US 34 west of Loveland) out of about 750 slopes rated on State Highways. Similar to the I-70 rockfall hazard, sources on the Highway 145 spurs

[2] **Hazard** is the potential to cause harm.
[3] **Risk** is the likelihood of harm.

come from far above the cut area. By comparison, the RHRS rating on Highway 145 ranges from 147 to 273 (Table 1). The exposure at Georgetown is greater due to average daily traffic (ADT) count of 30,000 vehicles or 21 vehicles each minute, compared to the Highway 145 West Spur ADT of 10,000 and the East Spur ADT estimated at 200. Between 1999-2008, there have been seven fatalities on Colorado Interstates or state highways as a result of rocks hitting cars and many instances of highway closures due to rockfalls. Currently, the Colorado Transportation Commission allocates $3 million statewide for rockfall mitigation each fiscal year.

CDOT's highest rating on Highway 145 is on Keystone Hill at milepost 97.1, which ranks 19th in the state with a rating of 552. This section of highway also includes 7 other segments with RHRS scores ranging from 543 to 186 and corresponding rankings from 24th to 647th in the state.

Figure 16 shows the segments of the East and West Spurs that were rated using the RHRS. Table 1 lists the components and total scores for each segment of roadway. Figure 17 shows a histogram comparing the RHRS scores for the 145 Spurs and all state highways. The 145 Spurs range from 147 to 273. According to Lawrence Pierson, the principal author of the original RHRS in the State of Oregon, slopes with a rating of less than 300 are assigned a very low priority while slopes with a rating in excess of 500 are identified for urgent remedial action (Ref. 3). According to this criterion, the Highway 145 East and West Spurs have a "very low priority" for remedial action.



Aerial photo source: San Miguel County GIS Dept. 1996 USDA Photo

Figure 16 - Rockfall Hazard Rating Segments on Highway 145 Spurs

Table 1 - RHRS Ratings for East & West Spurs

	1	2	3	4	5	6	7	8	9	10	11	12
Factor	Airport	Dakota	Eider Cr.	Mill Cr.	E San Miguel	Brewery	Town	Cemetary	Liberty Bell	Royer	Bridal Veil	Pandora
Slope Ht.	81	81	81	81	81	81	81	81	81	81	81	81
Slope Inclination	9	9	9	9	9	9	9	9	9	9	9	9
Launching Features	27	27	9	3	3	3	3	3	9	3	9	3
Ditch Catchment	9	27	81	3	27	3	3	3	3	3	27	3
Block Size	9	9	3	3	27	3	3	3	27	9	27	9
Quantity per Event	9	9	9	3	27	9	3	3	9	3	27	3
Precip./ Climate	27	27	27	27	27	27	27	27	27	27	27	27
Geology - Structural Conditio	9	9	9	3	27	9	3	3	27	9	27	3
Geology - Differential Erosior	27	27	27	3	27	9	3	3	27	3	27	3
% Site Distance	3	3	3	3	3	3	3	3	3	3	3	3
ADT	9	9	9	9	9	9	9	3	3	3	3	3
Number of Accidents	3	3	3	3	3	3	3	3	3	3	3	3
Observed Rockfall History	3	3	3	3	3	3	3	3	3	3	3	3
Total Score	225	243	273	153	273	171	153	147	231	159	273	153

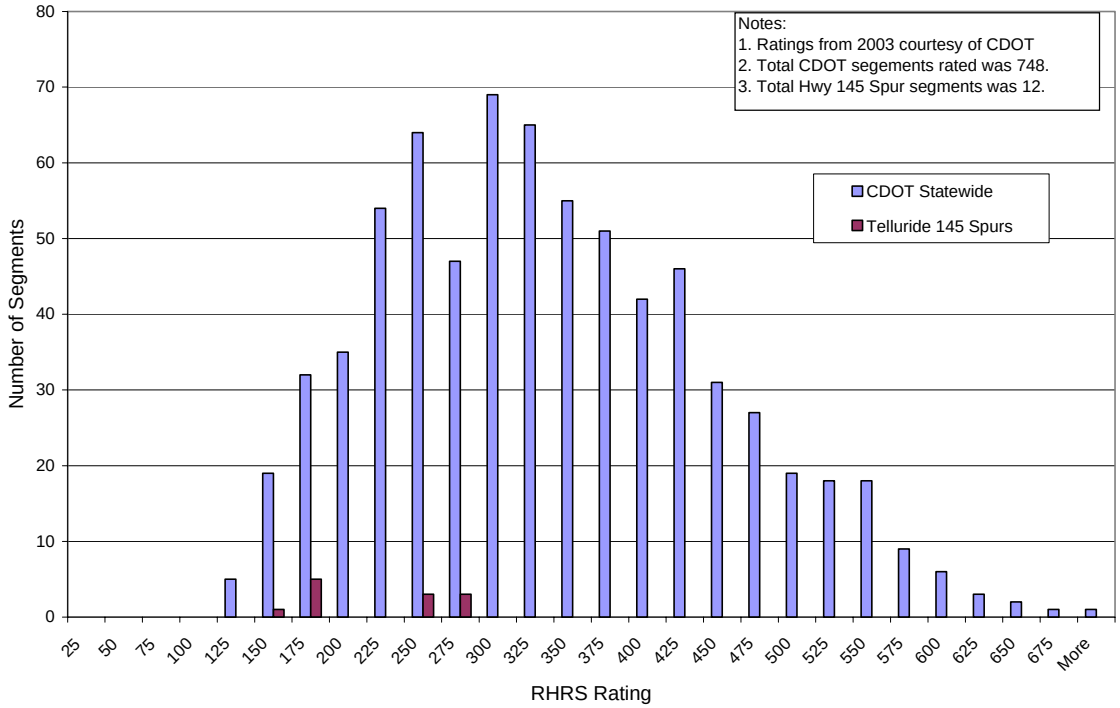


Figure 17 - Histogram of RHRS for E & W Spurs and State Highways

7. Mitigation

Complete mitigation of rockfall hazards is neither practical nor possible. Any mitigation effort must be aimed at reducing the hazard with the understanding that it cannot be completely eliminated. This situation exists for two reasons: first, the movement of most rocks cannot be predicted with certainty; and second, the costs of eliminating all rockfall would be extremely large. Additional social, political and environmental constraints also limit available mitigation options.

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Avoidance

Avoiding rockfall hazards is the most reliable method of mitigation but is not always possible. In Telluride, a significant portion of the existing developed town lies within a rockfall hazard area. The right-of-way for the East and West Spurs is established and it would be impractical and not justified to realign the roads, based on the findings of Section 6 of this study. For new development in areas of significant rockfall hazard, avoidance should be considered as the most reliable mitigation option.

Scaling

Scaling involves deliberate dislodging of unstable rocks such that rockfall events will occur at a controlled time. Scaling is a proactive rockfall management tool that is only appropriate where resources in the path of rockfall can be protected. *Scaling above developed areas is not recommended due to the high risk of causing substantial property damage.*

Scaling in areas where rockfall has the potential to reach the East and West Spurs might result in a slight reduction in the risk to the roadway. However, due to the very low incidents of historic rockfall events, the long sight distances and the lack of any accidents caused by rockfall, *we do not believe that scaling is warranted above the town's roadways*.

Direct Anchoring

Potential rockfall slopes are sometimes drilled and anchored in place to prevent rockfall. Our observations revealed many large rocks that appear to be marginally stable, particularly where differential erosion has resulted in overhanging blocks of Entrada sandstone. In our opinion, due to the nature of the erosion processes, anchoring would delay inevitable rockfall events and, potentially cause the rockfall events to be larger and more destructive. Also, there is a significant risk of inadvertently dislodging rocks and creating a rockfall event or multiple rockfalls during the anchoring operations. *Anchoring is not recommended.*

Net Anchoring (Draping)

Installation of wire-rope nets covering rockfall source areas has been widely used along highways to prevent small-to-medium sized rocks from reaching a roadway surface. It usually requires removal of the larger rocks prior to installation of the system. Since the primary rockfall concern within the study area is rockfall consisting of large blocks, draping does not offer significant reduction of rockfall hazard. *Draping is not recommended.*

Rockfall Fences

Rockfall catching structures (usually flexible wire-rope nets) have been field tested extensively in central Europe and have proven capable of dissipating rockfall kinetic energies of up to 5000 kJ (2,000 ft-tons) . Fences capable of lesser energy absorption have been installed at Telluride and have proven effective. The most feasible location for installation of rockfall catching barriers would be on the gentle slopes, if available, or close to the facilities to be protected. Application of the CRSP model to rockfall areas above Town (see Section 6) calculated energies up to 500 ft-tons (assuming a 90% exceedence probability) and bounce heights up to 11 feet. Rockfall energies and bounce heights decrease substantially with distance from the toe of the slope. The effectiveness of rockfall fences to protect down-gradient resources is highly dependent on site specific conditions, and thus requires site specific analyses. However, our general analyses indicate that rockfall fences above exposed structures on the north side of town would be effective and would reduce rockfall hazard by about 80% or more. Total installed costs for recently installed rockfall fences have ranged from about $500 to $1000 per lineal foot. Construction costs are dependent on fence height, length and access to construction sites. Maintenance costs vary depending on frequency and size of rockfall impacts. *Rockfall fences are technically feasible and may be an appropriate rockfall risk reduction measure for protecting Zone A (High Rockfall Hazard areas) where human exposure is significant and other resources are at risk.*

(a)

(b)

Figure 18 - Rockfall Fences (a) Telluride School (b) Idarado Legacy

Structure & Architectural Designs

Recent residential development in Telluride has relied upon direct structural reinforcement as the primary method of rockfall risk management within town. Exposed walls and roofs have been designed and constructed to resist rockfall impacts from small to medium size rocks. Also, placements of doors and windows and non-occupied spaces have been designed to reduce risk exposure. These measures are prudent and effective risk reduction tools, but they do not always provide the high level of protection that most people expect in their homes. These

methods do not protect areas or people outside of the buildings. *We recommend requiring site and structure specific designs for rockfall impacts on all habitable buildings within Zones A and B of the Rockfall Hazard Maps.*

Record Keeping

Careful documentation of rockfall events affecting the town and its resources are essential for modern risk-based hazard mapping. The location, time, date, rock size and shape and impacts of rockfall events should be documented, including photographs. If possible, source areas and travel paths should be mapped. *We recommend developing a form or checklist for documenting all rockfall events affecting the town and the East and West Spurs.*

Land Use Planning

Land use planning is an effective tool for managing risks associated with rockfall hazards. Changes in land use often increase the exposure to rockfall hazards. Also, new structures can reduce the hazard to down-gradient resources. *We recommend requiring site specific quantitative studies for all annexations and land use changes within mapped rockfall hazard zones.*

8. Town Owned Resources

Water Tanks

The town's potable water supply tanks north of the Tomboy Road east of Cornet Creek are not exposed to significant rockfall hazard at the present time. The hazard and risk could increase with changing conditions such as erosion resulting from a water line break above the tanks. Erosion could expose and destabilize rocks increasing the likelihood of rockfall. *We recommend monitoring conditions for erosion in the event of a water line break or following torrential rainfall events in the water tank area.*

Town Park Stage

The park and stage area lie below limited outcrops of the Entrada Sandstone that can produce rockfall on the south side of the valley. However our site observations indicate this area is not exposed to significant rockfall hazard at the present time. Slopes below the source area support a mature conifer and aspen forest. Trees will intercept, stop, divert and decelerate falling rocks except for any large, detached and extremely unusual blocks that do not break into smaller pieces. The Bear Creek access road and trail cuts will provide an additional stopping area for rocks and the low-gradient transition above the stage would also minimize rockfall travel distance and energy. *We recommend either preserving the vehicle access at the base of this slope or site-specific rockfall mitigation designs for structures encroaching on this corridor.*

9. Acceptable Risk

Risk is the measure of the probability and severity of an adverse effect to life, health, property, or the environment. The maps accompanying this report are "risk-based," meaning the probability of risk to persons or facilities has been considered. Quantification of risk is the ultimate goal, but the intermittent and unpredictability of rockfall events causes this to be very

difficult. The risk to permanent structures such as buildings and public or private property within the Town limits and their occupants is significantly higher than the risk to motorist, bicyclists and pedestrians on roadways. This is true due to the time of exposure to the hazard on roads and bike trails.

Risk on a roadway can be calculated by the following equation:

$$P(A) = fhP(S:H)P(T:S)P(L:I)$$

where:

P(A) is the annual probability of death of one occupant of a vehicle;
fh is the annual frequency of rockfall within the given sector of road;
P(S:H) is the longitudinal encounter probability,
P(T:S) =1.0 is temporal probability (continuous traffic)
P(L:I) is the probability of death, given an impact (vulnerability).

We made estimates of the various factors listed above to calculate the risk to the East and West Spurs and to residential areas within Zone A of the Rockfall Hazard and Risk Maps. Table 2 lists assumptions and calculated annual probability of death for residential areas within Zone A and for the East and West Highway 145 Spurs.

Table 2 - Rockfall Risk of Death Probabilities

Location	Avg. Return Period (years)	ADT	Longitudinal Exposure	Est. Prob. of death/event	Annual Probability of Death
Zone "A" Residential	25	N/A	75%	5%	0.00150
West Spur	50	10,000	4.5%	15%	0.00014
East Spur	10	200	0.2%	25%	0.00004
Other Risk Levels					
Lightning Death (Colo.) source: NOAA					0.000001
Auto Death (USA) source: National Hwy. Transportation Safety Board					0.00012
Acceptable risk for one death below a large dam source: BC Hydro					0.00010

The annual probability of death values presented in Table 2 should be viewed in terms of order of magnitude and compared to published values of acceptable risk. The risk levels for death caused by lightning and automobile are for an individual, whereas the probability estimates for rockfall are for a single death of any person. The acceptable risk below a large dam can be compared more directly because it refers to any person. Note that residences within the Zone A rockfall hazard area may have an annual probability of death about 10 times the acceptable risk for settlements below large dams. This finding indicates that proactive management of rockfall risk is warranted within the Zone A rockfall hazard area.

The probabilities in Table 2 indicate that high cost measures for rockfall mitigation along the East and West Spurs are not justified. Costs associated with 100% rockfall protection are usually unreasonably high. They often include acquisition of the right of way, large excavation and construction cost. The adverse environmental impact and cost usually cannot be justified.

10. Rockfall Hazard Ordinance

We reviewed the existing Telluride Rockfall Hazard Ordinance. The intent and purpose of the Ordinance remain unchanged. However, it is our opinion that this ordinance can be updated based on better knowledge and understanding of rockfall process, hazards and risks. We recommend the following changes:

1. Adopt the rockfall hazard areas, Zone A and Zone B, from this study.
2. Require site and structure-specific quantitative rockfall studies for all new or substantially improved habitable structures within Rockfall Hazard Zone A and Zone B. Reword Section 8-524.C item 1 to reflect this recommendation.
3. Require structural and architectural designs based on the findings of item 2 for all new or substantially improved habitable structures within Zone A. Mitigation measures for Zone B should be advisory, rather than mandatory, and based on the findings of the site specific study.
4. Delete the reference to cementing (8-524.C, item 2) of rockfall sources in place.

There are additional factors affecting rockfall hazard that should be considered, but not necessarily included in the Ordinance:

1. We do not know how many or which structures with Rockfall Hazard Zone A have incorporated structural or architectural measures to reduce rockfall risk.
2. New rockfall resistant structures may have the effect of reducing rockfall risk for other down-gradient structures.

11. References

General References:

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Previous Telluride Rockfall Studies

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2. Letter to Bill Gordon, Atlas Constructors from Buckhorn Geotech Consulting Engineers, Price Res., Lots 17-20, Dakota Addition – October 21, 1987
3. Rockfall Hazard to the North Telluride Hillside Property, Lots 7 and 8, David P. Groenveld, Ph.D., 1987
4. Letter to Richard Van Asperen from Buckhorn Geotech Consulting Engineers. August 29, 1990. Petty Residence, Lot 2, Mill Placer, 106 Tomboy Rd.
5. Report of Development Feasibility and Geological Hazards, Lots 3-10, Blk 2, E. Telluride Addn. Buckhorn Geotech, 12.18.90
6. Geologic Hazard Analysis, McCreedy Res. 488 Tomboy Rd. Lots 1,2 Blk C, N Telluride Addn. Buckhorn 10.18.91
7. Telluride High School Site Geologic Hazards Report, Buckhorn Geotech, 1993
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9. Letter to Todd Creel from Western Technologies dated July 6, 1998, Creel Res. Lots 7/8, Block 13, Telluride.
10. Geotechnical Engineering Study for Holgren Res., Lot 6, Brewery Subdiv. Lambert & Associates, November 18, 1998.
11. Letter to Todd Creel from Buckhorn Geotech dated April 21, 1999 on Geological Hazards, Lots 7 and 8 Block 13, Telluride.
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13. Rockfall Inspection Report and Preliminary Assessment, March 8, 2000. Buckhorn Geotech Consulting Engineers.
14. Soil & geologic Hazard Investigation: Lot 2, Block A, Woody's Addn. Buckhorn Geotech, September 8, 2000.
15. Geotechnical Study for McCargo Res. by Lambert and Associates, March 11, 2002.
16. Rockfall Hazard and Mitigation Options, Proposed Telluride School Expansion, Arthur I. Mears, P.E., Inc. 2002
17. Letter to Connie Giles, Architect for McCargo Res. from Buckhorn Geotech dated December 31, 2002, Clarification letter for east side protection
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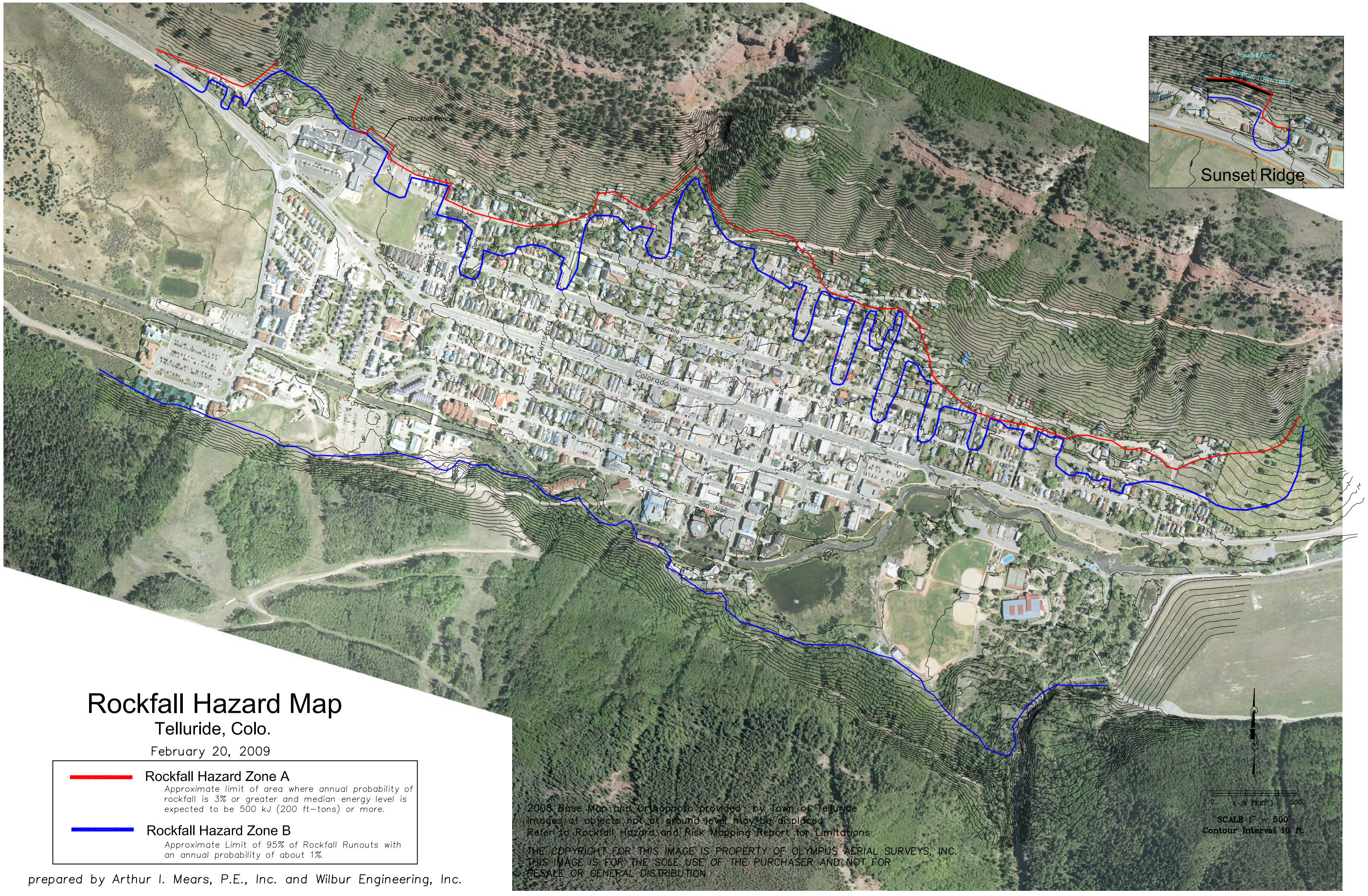
24. Geologic Hazards of the Telluride Area, San Miguel County, Colorado, 1977, by Patrick O'Boyle.
25. Proposed Sunset Ridge Development Rockfall Mitigation Comments, Lambert and Associates, November 11, 2002.
26. Geologic Hazards Report Pandora Water Project, San Miguel County, Colo. Buckhorn Geotech, November 30, 2007.

Interviews

1. Bill Mahoney, long-time Telluride resident.
2. Raymond Hughes, town public works employee 1972-2001.
3. Leroy Padilla, former miner, long time resident
4. Gary Bennett, long-time resident.
5. Ty Ortiz, CDOT Rockfall Mitigation Specialist
6. Gary Broderick, long-time Telluride resident and contractor
7. Mike Horner, San Miguel County Road & Bridge



Rockfall Hazard Map

Telluride, Colo.

February 20, 2009

Rockfall Hazard Zone A

Approximate limit of area where annual probability of rockfall is 3% or greater and median energy level is expected to be 500 kJ (200 ft–tons) or more.

Rockfall Hazard Zone B

Approximate Limit of 95% of Rockfall Runouts with an annual probability of about 1%.

prepared by Arthur I. Mears, P.E., Inc. and Wilbur Engineering, Inc.