Mears 1997.

DESIGN-MAGNITUDE AVALANCHE MAPPING AND MITIGATION ANALYSIS

KIRKWOOD RESORT, CALIFORNIA

-- AN UPDATED STUDY

Prepared For

Mr. Peter Eicher

Kirkwood Resort

Prepared By

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Gunnison, Colorado
October, 1997

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October 22, 1997

Mr. Peter Eicher
Kirkwood Associates, Inc.
P. O. Box 1
Kirkwood, CA 95646

Dear Mr. Eicher:

The attached updated study of design-avalanche extent and mitigation concepts in selected areas of Kirkwood has been completed as we discussed last month and during my site visit earlier this month.

Please contact me if you have any questions or desire additional consultation.

Sincerely,

Arthur I. Mears

Arthur I. Mears, P.E. (CO)
Avalanche-control engineer

Encl.

1 OBJECTIVES AND LIMITATIONS

As discussed with Mr. Peter Eicher of Kirkwood Associates and outlined in my proposal letter of August 29, I997, this report has the following **objectives**:

a. Mapping of the limits of design-magnitude avalanches;
b. Statistical and dynamics analysis of design-magnitude avalanches and subdivision of avalanche areas into red and blue zones;
c. Discussion of passive and active avalanche mitigation methods that can be used to eliminate or reduce the potential hazard.

This report also has the following **limitations** which must be understood by all those relying on the results and recommendations:

a. The study is valid only within the areas studied and shown on the topographic map (Figure 1) attached to this report;
b. Avalanches also will occur outside of the areas studied but have not been mapped;
c. Design-magnitude or "100-year" avalanche extent may be exceeded by extraordinary events with longer return periods; and
d. Final design loading criteria for structures that may be exposed within the avalanche zones have not been provided.

2 TERRAIN AND DESIGN-MAGNITUDE AVALANCHES

2.1 TERRAIN

The areas studied in this report, as outlined by Mr. Peter Eicher during the site inspection earlier this month, consists of two development parcels at the base of the Kirkwood Ski Area. These areas are labeled "A" and "B" on Figure 1, a 1" = 500' scale base map. Avalanche paths extending into areas A and B are also indicated on this map. Figure 1 does not include avalanche areas appearing on the "Design Avalanche Map" which accompanied my previous study "*Design Avalanche Mapping and Hazard Analysis*" submitted to Mr. Larry Kumpost of Kirkwood in November, 1995.

2.1.1 Development Area A

Development area A is located south of a existing subdivision cul-de-sac and is below approximately 8,000 feet elevation. Avalanche affecting area A begin in relatively small starting zones at 8,800 - 9,000 feet elevation, on the east, or lee side of the ridge north of Martin point. The area north of Martin Point can receive heavy and sometimes unstable snow accumulations. During some storm periods large amounts of snow can be deposited into the starting zones by west winds. Field evidence indicates that avalanches have previously extended downslope to at least the 8,200 foot elevation level, but there have been no historic observations or clear field evidence of avalanches descending into development area A.

Starting zones above area A will be increased in size somewhat by proposed cutting of ski trails north of the proposed Martin Point chairlift. Some of the cutting will take place on slopes of more than 25°-30° inclination between existing starting zones. This new clearing will increase the size and frequency of major avalanches somewhat and has been considered in the analytical procedures used in this report to map avalanches. The magnitudes of the rare or "design-magnitude" avalanches have been determined as discussed in Section 2.2.

2.1.2 Development Area B

Area B is located below the Olympic ski run and below lift 7 as indicated in Figure 1. It is situated between avalanche paths defined in the 1995 study. The Olympic Run avalanche has reached to approximately the 8,000-foot elevation level during the 1980's (pers. comm, Sheila Reuter) and has been considered a hazard sufficiently serious to move a ski patrol access trail to below the known avalanche runout. No changes to the avalanche starting zones are planned in the area, however the steep terrain served by lift #6 is known to produce large and sometimes spontaneous or "natural" avalanches as well as large avalanches released by explosive control.

Major or "design-magnitude" avalanches will extend downslope long distances near development area B because a) the terrain remains fairly steep (10° - 15°) in the runout zones and b) avalanches can, in some cases, become channelized in deep gullies. The design-magnitude avalanches, similar to those affecting area A, will exceed the limits of avalanches that have been observed at Kirkwood. The magnitudes of the rare or "design-magnitude" avalanches have been determined as discussed in Section 2.2.

2.2 DESIGN-MAGNITUDE AVALANCHES

2.2.1 Definition of the design-magnitude avalanche

Design-magnitude avalanches are of a size and destructive potential that must be considered in land-use planning and engineering. In the case of residential development at the base of the Kirkwood Ski Area, the design-magnitude avalanche has a return period on the order of 100 (or $10^{2.0}$) years. This is only a nearest order-of-magnitude (factor-of-ten) estimate of the true return period. The true return period, T, of the design-magnitude avalanche lies between the limits

$10^{1.5} < T$, $10^{2.5}$ years (roughly 30-300 years). This definition of the design-magnitude avalanche is relatively unique to the United States. Other countries with development in and near avalanche areas (e.g. Iceland, Norway) require avoidance of avalanches with return periods of up to 300 years. Development in Switzerland is permitted in areas with return periods of more than 30 years is avalanche defensive structures are used to reduce the hazard.

The return period T is reciprocally related to the annual probability P by the relationship T = 1/P. Therefore a 100-year event has a constant annual probability of 0.01 (1%). Avalanches with return periods of 100 years may occur on successive years or may not occur for 200 years or longer. Such rare events have rarely been observed at a given area, therefore they usually must be determined by indirect techniques such as those discussed in Section 2.2.2 of this report.

2.2.2 Mapping the design-magnitude avalanche at Kirkwood

Because the historic record at Kirkwood is only a quarter-century old and vegetation damage is in some cases difficult to interpret, especially where development, ski trails, or other construction have taken place, indirect procedures have been used to map the avalanches. Specifically, the following two-step procedure has been used.

a. Step 1. Avalanche *runout distance* or stopping position was determined by using a statistical regression equation based on a database of 90 major avalanches that have occurred in the eastern Sierra Nevada primarily during this century. Given observations of the past performance (runout distance; destructive effects) of these 90 avalanches, a regression equation was derived that predicts runout distance from measurable terrain parameters in the upper parts of the paths. By utilizing this regression analysis the stopping position of avalanches affecting areas A and B was predicted and transferred to the topographic map (Figure 1).
b. Step 2. Given the stopping position determined in Step 1, a physical avalanche-dynamics model was fit to the path profile, forcing the model to produce a stopping position at the statistically-determined runout zone limit. Avalanche "red" and "blue" zones were then defined as that point along the avalanche path profile where the impact pressure potential decreased to approximately 600 lbs/ft^2 (30 kPa). The relationship used to compute impact-pressure potential (kinetic-energy density) was $P = \rho V^2$, where P is pressure, ρ is avalanche density (150kg/m^3) and V is computed velocity (m/sec).

The derived data on avalanche runout limits described above was then compared with observed avalanche runout limits where they could be interpreted from vegetation damage on 1941 (pre-development) aerial photographs taken by the U. S. Forest Service. Interpretation of these photographs indicates that avalanches appear to have reached fairly close to the base of the slope at several locations. This supports the conclusions reached in the statistical/avalanche dynamics analysis.

The computer output that was used to compute velocities and impact-pressure potential is provided in the technical appendix of this report. The results have been projected onto the topographic map (Figure 1).

3 AVALANCHE MAP AND HAZARD ZONES

3.1 Mapped Areas

The 1" = 500' scale topographic map (Figure 1) delineates the design-magnitude or 100-year avalanche boundaries that should be considered in land-use planning and engineering. The boundaries of these avalanche paths were determined through application of the methods discussed in Section 2 of this report. *Avalanches have been mapped only in areas that affect specific development parcels as indicated by Mr. Peter Eicher during the October, 1997 site inspection.* See the previously-referenced 1995 study for mapping of some adjacent areas.

3.2 Hazard Zone Definitions

Design-magnitude avalanche path boundaries are subdivided into "red," blue," or "white" zones of potential hazard severity based on impact pressure and return period (i.e. frequency) criteria defined below.

a. **High Hazard (Red) Zones**. Avalanches in the red zone can 1) produce impact pressures of 600 lbs/ft^2 (approx. 30 kPa) or more on flat, rigid surfaces normal to the avalanche flow, *or*, have return periods T < 10 years, *or* 3) both "1" and "2." They are designated by an "R" on Figure 1.
b. **Moderate Hazard (Blue) Zones**. Avalanches in the Blue zone must 1) produce impact pressures of < 600 lbs/ft^2 (approx. 30 kPa) on a flat, rigid surface normal to the flow, *and*, 2) have return periods 10 < T < 100 years. Both conditions "1" and "2" must be satisfied or the area is disqualified as a blue zone and must be classified as a red zone. These areas are indicated by a "B" on Figure 1.
c. **"Hazard-Free (White) Zones**. These areas are beyond the range of the design-magnitude avalanche but could be reached by extreme avalanches with very long (> 100 year) return periods. Such

extremely rare events cannot be delineated because they lie beyond the range of experience, observations, or analysis available in the eastern Sierra Nevada mountains. White zones can also be reached by powder blast, near the outer boundaries of the blue zones.

The return period designations are no better than nearest "order-of-magnitude" estimates of the true return periods. Therefore a return period, T of 100 years may lie between the limits $30 < T < 300$ years; a return period of 10 years may lie between the limits $3 < T < 30$ years.

4 RECOMMENDED LAND-USES IN HAZARD ZONES

The land uses discussed and recommended in this section apply to snow avalanche red and blue zones. They are similar to those recommended in avalanche zones at other locations in the United States, Switzerland, and Austria but are *less conservative* than those recommended land uses in Norway and Iceland (e.g. Norway and Iceland avoid residential construction in areas exposed to 300-year avalanches).

4.1 **Red Zone use recommendations.** Residential development within the red zone is not recommended. Avalanche pressure potentials are beyond the practical design limits of most residential structures, avalanche frequency is high, and detached structural protection is difficult or impossible to build. Additionally, any development that concentrates human activity in red zones (ski-lift terminals, ticket areas, parking lots, trail heads, skating ponds, and public buildings) should be avoided. Even though structural protection of some facilities might be feasible, people standing or working outside of these facilities could be exposed to avalanches. Road construction through some red zones might be acceptable unless the frequency of avalanches is high. Utilities should be buried whenever possible.

4.2 **Blue Zone use recommendations.** By definition, blue zones are subject to much lower levels of avalanche frequency and energy than red zones. Thus construction of private buildings may be acceptable, but only if reinforced or protected for design avalanche loads. Even with structural protection, property owners must be made aware of the fact that living in an area designated as a blue zone means assuming the possibility of property damage or personal injury from avalanches because people outside may be exposed. Because of the potential for a greater concentration of people at public facilities, construction of public buildings in blue zones should be avoided. Other public facilities such as parking lots and ski-lift terminals should, if possible, be located near the outer limits of the blue zone and the area should be posted as potentially hazardous. As recommended in

Section 4.1, utilities should be buried. Road construction is acceptable because of the relatively long return period in the blue zone.

5 AVALANCHE MITIGATION

5.1 AVOIDANCE

Although mitigation, including land-use planning and structural control, can be used to reduce the potential hazard to a level acceptable to some public and private entities at some locations, the risk from extremely rare or unprecedented avalanches cannot be completely avoided. An analysis of the type completed in this study has certain inherent uncertainties in specifying the behavior, impact pressures, directions, and exact stopping positions of major avalanches. Therefore, *complete avoidance of buildings or facilities that concentrate human activity (e.g. residential construction, public facilities) is the recommended form of mitigation in both red and blue zones.*

5.2 STRUCTURAL MITIGATION

Structural avalanche control is the recommended form of mitigation in blue zones when the design avalanche cannot be completely avoided. Details of the structural control options are beyond the scope of this study because such details depend upon planned type and location of facilities. However, the types of mitigation feasible at Kirkwood are summarized below. Site specific study at each location will be required to determine the most suitable form of mitigation.

a. Direct-protection structures. Direct-protection structures can provide complete protection for objects (e.g., buildings, ski-lift towers, etc.) that are exposed to avalanches. They can be designed and built on an individual basis and often do not require large amounts of material or space. Buildings can be reinforced for avalanche loads and oriented to reduce avalanche forces. With proper design criteria established, this method could be used within the blue zone at some Kirkwood sites.
b. Deflecting structures. Deflection structures intercept and deflect avalanches at small angles to their natural flow directions and divert the snow away from the objects to be protected. They do not necessarily shorten runout distance. Such structures are most effective when they enhance the natural terrain features.
c. Retarding mounds. Mound shorten runout distances by creating additional friction between the avalanche and the ground, spreading avalanches laterally and reducing flow height, velocity, and pressure potential. Although they have been effective in shortening the runout

distance of the dense core of flowing avalanches, they do little to shorten the runout distance of fast-moving powder avalanches.

d. Catching dams. Dams reduce the runout distances and can sometimes be used in place or in conjunction with mounds. They are similar in form to deflecting berms but are built perpendicular to the flow direction because they are intended to stop rather than deflect the snow. Storage for avalanche snow must be provided on the uphill side of the dam. Catching dams will not be effective against fast-moving powder avalanches.

The four principal types of avalanche mitigation discussed above, although applicable at selected areas of Kirkwood, will all require careful study to determine the design parameters (avalanche velocity and flow height, structure location, orientation, shape and size, and terrain details. The designation of red and blue zones on the avalanche map does not provide the necessary design criteria.

5.3 AVALANCHE FORECASTING AND CONTROL

In addition to land-use planning and structural control, a number of non-structural avalanche mitigation methods have been used worldwide with varying success. These hazard management methods include avalanche forecasting, explosive control, use of restricted travel, evacuation, and rescue contingency plans. None of these methods work as well in developed areas as avoidance or structural control in reducing hazard to an acceptable level.

Although operational avalanche forecasting and control procedures are essential and nearly always effective in reducing the hazard at a ski resort or on a highway, they will sometimes produce the unexpectedly large avalanche one wishes to prevent. The design avalanche, in particular, because of its long return period, may result from conditions that operational avalanche forecasters are not familiar with. Although the objective of operational control methods is to reduce and manage the size and timing of avalanches, history has shown that such attempts at hazard management simply do not always work. Extremely large avalanches have been inadvertently triggered (or not prevented) at many locations. Because of the uncertainties associated with avalanche forecasting and control methods, they are not recommended as a method to protect valuable facilities or occupied structures. Therefore, they should not be used in avalanche paths capable of reaching occupied areas at Kirkwood.

Report prepared by,

Arthur I. Mears

Arthur I. Mears, P.E. (CO)
Avalanche-control engineer

TECHNICAL APPENDIX

The results of the physical modeling procedures used in this study follow. Avalanche stopping position was determined by the indirect techniques, including statistical modeling discussed in section 2 of this report. Physical modeling was then used to calculate velocities along the avalanche path centerline and calculate impact pressure potential. The results of the modeling were used to compute the boundary between the red and blue zones. Velocity data derived could be used in future studies to design mitigation, if desired.

Avalanche paths labeled 97A and 97B can produce avalanches capable of reaching portions of development area "A." Paths 97C, 97D, and 97E are above development area "B."

The following details are available in the computer modeling output the follows in the next two pages:

SEGMENT --	Segment of the avalanche path
LENGTH --	Length of the segment (m)
ANGLE --	Vertical angle of the segment
MU --	Coefficient of dynamic (sliding) friction
M/D (M) --	Mass-to-drag ratio (m) used in analysis
V(top) --	Velocity (m/sec) at top of each segment
V(bottom) --	Velocity (m/sec) at bottom of each segment

KIRKWOOD SKI AREA: Path 97A

INPUT DATA

SEGMENT	LENGTH(m)	ANGLE	MU	M/D(m)
0	36.0	31.0	0.25	1300
1	98.0	29.7	0.25	1300
2	99.0	21.8	0.25	1300
3	121.0	20.7	0.25	1300
4	96.0	18.4	0.25	1300
5	115.0	12.2	0.25	1300
6	40.0	8.7	0.25	1300
7	155.0	11.3	0.25	1300
8	96.0	11.0	0.25	1300
9	86.0	8.1	0.25	1300

VELOCITIES

SEGMENT	V(top)	V(bottom)
0	0.0 m/s	14.4 m/s
1	14.4 m/s	26.0 m/s
2	25.7 m/s	28.6 m/s
3	28.6 m/s	30.6 m/s
4	30.6 m/s	30.7 m/s
5	30.6 m/s	26.7 m/s
6	26.7 m/s	24.4 m/s
7	24.4 m/s	18.3 m/s
8	18.3 m/s	14.0 m/s
9	13.9 m/s	1.4 m/s

Avalanche does not stop.

KIRKWOOD SKI AREA: Path 97B

INPUT DATA

SEGMENT	LENGTH(m)	ANGLE	MU	M/D(m)
0	96.0	34.7	0.25	1200
1	59.0	38.7	0.25	1200
2	36.0	31.0	0.25	1200
3	117.0	24.6	0.25	1200
4	76.0	23.5	0.25	1200
5	138.0	18.0	0.25	1200
6	78.0	13.5	0.25	1200
7	106.0	13.2	0.25	1200
8	233.0	8.1	0.25	1200
9	86.0	8.1	0.25	1200

VELOCITIES

SEGMENT	V(top)	V(bottom)
0	0.0 m/s	25.1 m/s
1	25.1 m/s	32.4 m/s
2	32.1 m/s	34.3 m/s
3	34.1 m/s	36.7 m/s
4	36.7 m/s	37.7 m/s
5	37.6 m/s	36.0 m/s
6	35.9 m/s	33.4 m/s
7	33.4 m/s	30.1 m/s
8	30.0 m/s	14.3 m/s
9	14.3 m/s	3.3 m/s

Avalanche does not stop.

KIRKWOOD SKI AREA: Path 97C

INPUT DATA

SEGMENT	LENGTH(m)	ANGLE	MU	M/D(m)
0	120.0	30.5	0.25	750
1	150.0	26.6	0.25	750
2	109.0	30.1	0.25	750
3	99.0	17.9	0.25	750
4	141.0	12.5	0.25	750
5	117.0	9.0	0.25	750
6	70.0	5.0	0.25	750

VELOCITIES

SEGMENT	V(top)	V(bottom)
0	0.0 m/s	24.2 m/s
1	24.2 m/s	30.6 m/s
2	30.6 m/s	35.0 m/s
3	34.3 m/s	31.9 m/s
4	31.8 m/s	25.1 m/s
5	25.1 m/s	16.8 m/s
6	16.7 m/s	5.5 m/s

Avalanche does not stop.

KIRKWOOD SKI AREA: Path 97D

INPUT DATA

SEGMENT	LENGTH(m)	ANGLE	MU	M/D(m)
0	67.0	39.5	0.30	850
1	65.0	27.8	0.30	850
2	145.0	24.9	0.30	850
3	136.0	15.6	0.30	850
4	175.0	12.1	0.30	850
5	114.0	15.5	0.30	850

VELOCITIES

SEGMENT	V(top)	V(bottom)
0	0.0 m/s	22.2 m/s
1	21.7 m/s	25.3 m/s
2	25.3 m/s	28.5 m/s
3	28.2 m/s	23.0 m/s
4	23.0 m/s	10.7 m/s
5	10.7 m/s	6.7 m/s

Avalanche does not stop.

KIRKWOOD SKI AREA: Path 97E

INPUT DATA

SEGMENT	LENGTH(m)	ANGLE	MU	M/D(m)
0	63.0	29.1	0.30	700
1	49.0	29.7	0.30	700
2	85.0	30.3	0.30	700
3	115.0	25.2	0.30	700
4	65.0	27.8	0.30	700
5	145.0	24.9	0.30	700
6	136.0	15.6	0.30	700
7	175.0	12.1	0.30	700
8	114.0	15.5	0.30	700

VELOCITIES

SEGMENT	V(top)	V(bottom)
0	0.0 m/s	15.9 m/s
1	15.9 m/s	20.8 m/s
2	20.8 m/s	26.5 m/s
3	26.4 m/s	28.2 m/s
4	28.2 m/s	29.9 m/s
5	29.9 m/s	30.6 m/s
6	30.2 m/s	24.0 m/s
7	23.9 m/s	11.0 m/s
8	11.0 m/s	6.8 m/s

Avalanche does not stop.

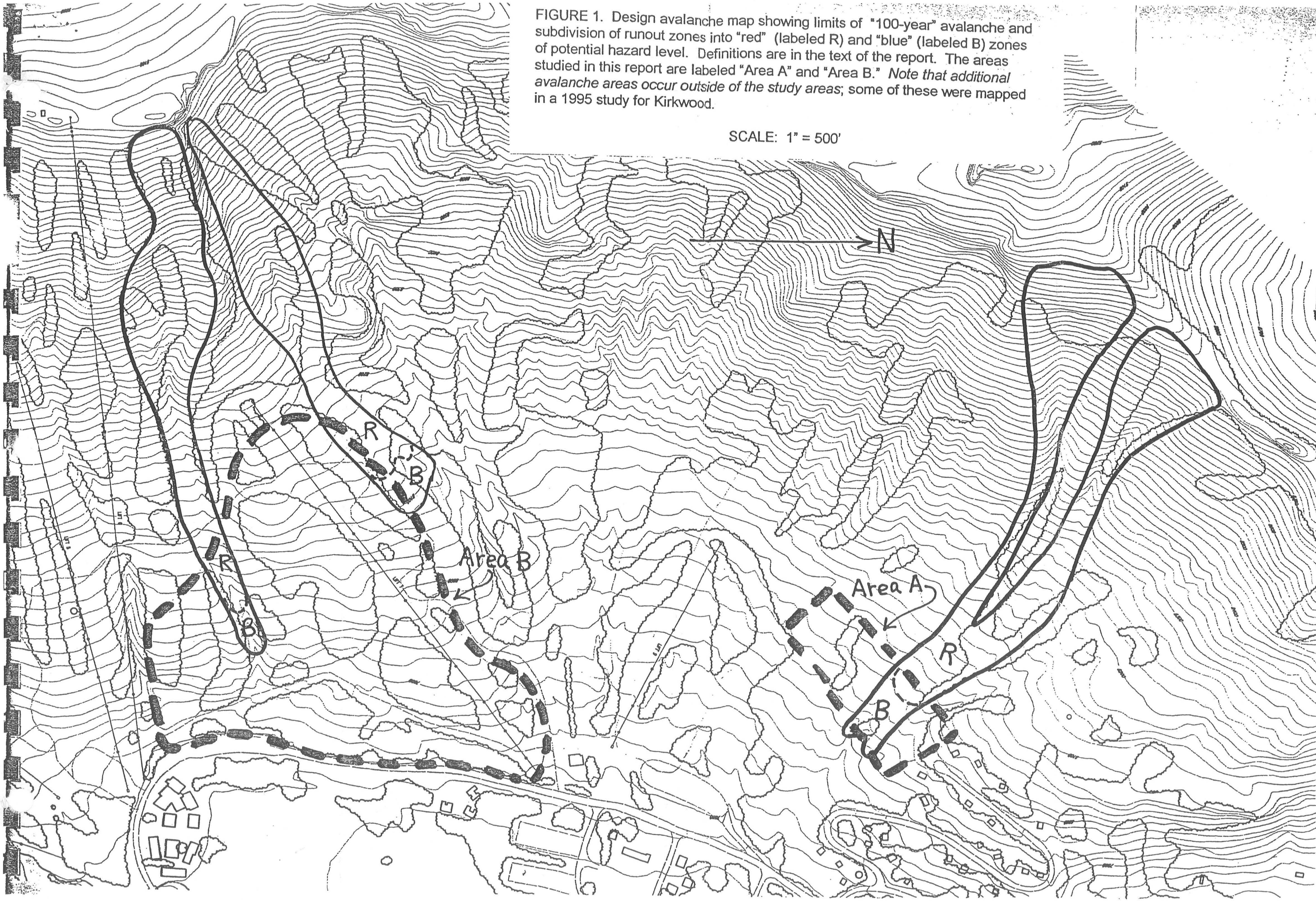

FIGURE 1. Design avalanche map showing limits of "100-year" avalanche and subdivision of runout zones into "red" (labeled R) and "blue" (labeled B) zones of potential hazard level. Definitions are in the text of the report. The areas studied in this report are labeled "Area A" and "Area B." *Note that additional avalanche areas occur outside of the study areas*; some of these were mapped in a 1995 study for Kirkwood.

SCALE: 1" = 500'