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Estimating debris-flow probability using fan stratigraphy, historic records, and drainage-basin morphology, Interstate 70 highway corridor, central Colorado, U.S.A.

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ABSTRACT: We have used stratigraphic and historic records of debris-flows to estimate mean recurrence intervals of past debris-flow events on 19 fans along the Interstate 70 highway corridor in the Front Range of Colorado. Estimated mean recurrence intervals were used in the Poisson probability model to estimate the probability of future debris-flow events on the fans. Mean recurrence intervals range from 7 to about 2900 years. Annual probabilities range from less than 0.1% to about 13%. A regression analysis of mean recurrence interval data and drainage-basin morphometry yields a regression model that may be suitable to estimate mean recurrence intervals on fans with no stratigraphic or historic records. Additional work is needed to verify this model.

1 INTRODUCTION

Interstate 70 (I-70) in Colorado is the main east-west transportation route serving the Denver metropolitan area, one of the fastest growing regions in the United States. Increasing traffic associated with the population growth has led to traffic congestion on I-70 east of the Continental Divide, along the mountainous Front Range portion of the highway (Fig. 1). Desire to alleviate this congestion has motivated recent investigations into modifications of transportation infrastructure that would increase the capacity along the Front Range portion of the I-70 corridor (Andrew & Lovekin 2002, Arndt et al. 2002). Modifications that have been proposed include additional highway lanes, an additional highway tunnel under the Continental Divide (there are currently two which are jointly referred to as the Eisenhower Tunnel), and a monorail. Assessments of geologic hazards in the corridor provide critical baseline information that can be used to evaluate the proposed modifications (Andrew & Lovekin 2002).

Recent and historic debris flows, as well as Holocene debris-flow deposits, show that the Front Range part of the I-70 corridor is susceptible to debris-flow hazards (Hecox 1977, Pelizza 1978, Coe et al. 1998, Soule 1999, Widmann et al. 2000, Coe et al. 2002, Godt & Coe 2003, Andrew & Lovekin 2002). However, the likelihood of future debris-flow occurrence at individual fans in the corridor has not been addressed.

In this paper, we use subsurface exposures and historic records of debris-flow events to estimate mean debris-flow recurrence intervals and probability of future debris-flow occurrence on 19 fans in the Front Range portion of the I-70 corridor. We also present a regression model that correlates mean recurrence interval with drainage-basin morphometry. This model makes it possible to estimate mean recurrence intervals at fans where there are no subsurface exposures or historic records, but the model needs to be verified by additional work.

2 SETTING

The Front Range part of the I-70 corridor that is the focus of this study is a 45 km section between the Eisenhower Tunnel and Floyd Hill (Fig. 1). Along this section, I-70 parallels Clear Creek, a perennial, east-flowing, formerly glaciated drainage. Debris flows in this section of the corridor initiate in tributaries of Clear Creek and form fans along the north and south flanks of the Clear Creek valley. Near the center of the study area is a boundary of maximum Pleistocene glaciation (Madole et al. 1998). The valley above this boundary contained Pleistocene glaciers and is U-shaped, with steep valley walls and generally small and steep tributary basins (Figs. 2b, c). The valley below the boundary was not glaciated and is V-shaped with less steep valley walls and generally large tributary basins with moderate relief (Fig. 2a).

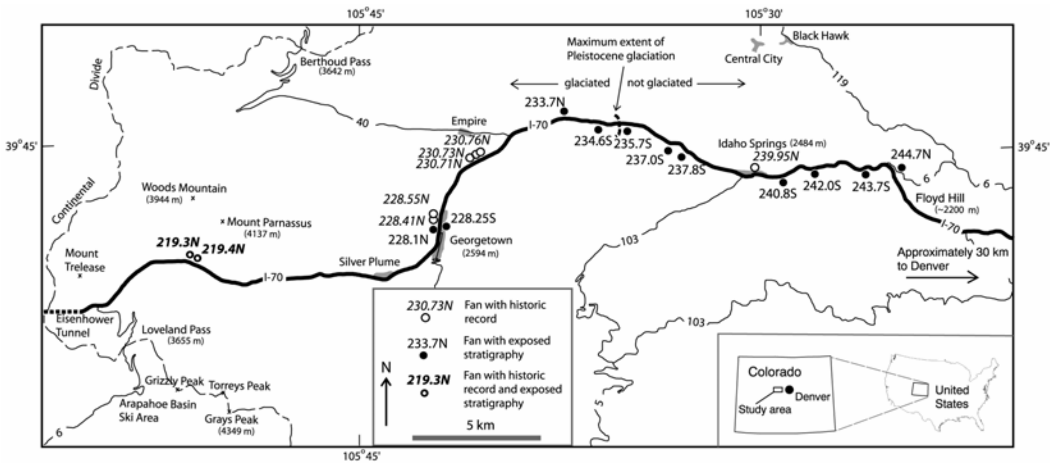

Figure 1. Map showing study area and location of fans. The study area is within the north-south trending Front Range, the eastern-most mountain range in Colorado. Fans are named according to their position with respect to highway mile markers. Letters N and S in fan names designate fan position on the north or south side of the highway, respectively. Shaded areas are towns. Road and highway numbers are labeled and selected elevations are shown in parentheses.

Elevations within the Clear Creek valley range from about 2200 m at Floyd Hill to about 3350 m at the east entrance to the Eisenhower tunnel. Mountain peaks adjacent to the Clear Creek valley range up to about 4350 m in elevation. Mean annual precipitation ranges from about 380 mm in Idaho Springs (elevation 2484 m) to about 840 mm at the Arapahoe Basin Ski Area (elevation 3642 m) near the Eisenhower Tunnel (Western Regional Climate Center, unpublished data). Most recent and historic debris flows in the area have been triggered by thunderstorms related to the flow of monsoon moisture (known as the Southwest, Mexican, or North American monsoon, Adams & Comrie 1997) from the south in late summer (Coe et al. 2002, Godt & Coe 2003).

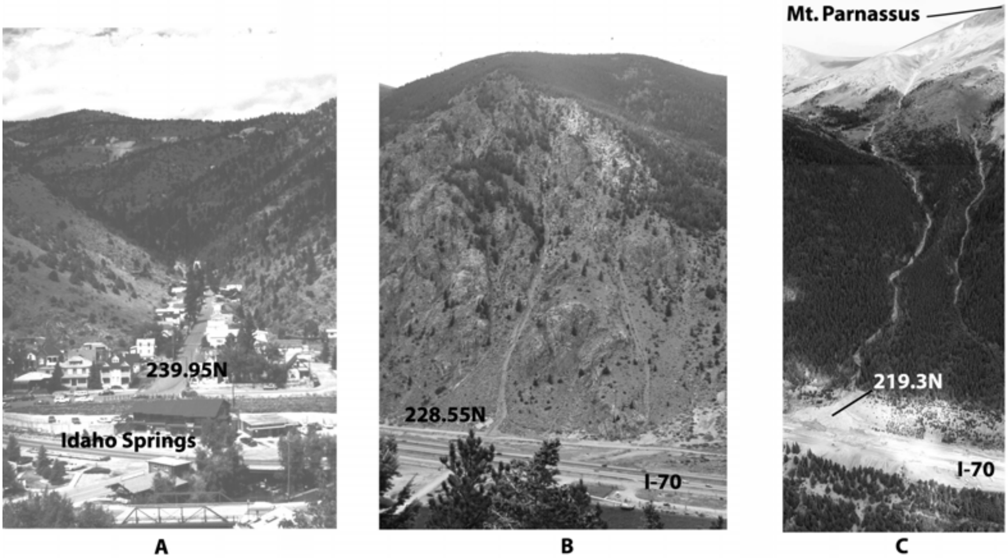

Figure 2. Examples of drainage basins upslope from fans in the study area. A) Basin above fan 239.95N, a flood-dominated fan below the maximum extent of Pleistocene glaciation. Melton's number (see text for explanation) for this basin is 0.256. Photo was taken in 1997. B) Basin above fan 228.55N, a debris-flow dominated fan above the maximum extent of glaciation that has had multiple debris-flow events in the last several decades. Melton's number for this basin is 1.750. Photo was taken on August 30, 1996. C) Basin above fan 219.3N, a debris-flow dominated fan above the maximum extent of glaciation and the site of a debris-flow event that covered I-70 on July 28, 1999. Melton's number for this basin is 0.479. Photo was taken by Ed Harp on July 29, 1999.

Tree cover in the area ranges from predominantly Ponderosa Pine and Juniper trees at lower elevations to Lodgepole Pine and Engleman Spruce at higher elevations. Tree line is at an elevation of about 3500 m. Above tree line, hillslopes are bare or are covered by alpine tundra (see Fig. 2c). In general, hillslopes and drainage basins on the south side of I-70 (north facing) have more vegetation than hillslopes and basins on the north side (south facing) of I-70. All recent and historic debris flows have initiated in drainage basins on the north side of I-70.

The study area is underlain predominantly by Precambrian gneiss but also by scattered Tertiary intrusions (Bryant et al. 1981) with associated hydrothermal alteration and mineralization (Tweto & Sims 1963). The zone of mineralization that encompasses the study area extends from southwestern Colorado to the Front Range northwest of Denver, and is known as the Colorado Mineral Belt (Tweto & Sims 1963). Mining activity was common in the area in the late 1800s and early 1900s and numerous abandoned mines and mine dumps are present on hillslopes in the area.

The presence of I-70 in the Clear Creek valley is both an advantage and disadvantage for debris-flow hazard assessments. It is an advantage because highway construction activities created cuts through many fans, either by direct excavation for installation of highway lanes, or by excavation as a source of fill material. These cuts provide subsurface exposures of fans that can be used to study debris-flow history. Disadvantages are related to the fact that, like many roads in Colorado, I-70 runs along the north side of the valley, presumably to take advantage of southerly exposure to quickly melt snow and ice on the highway surface. Many of the fans along the north side have therefore been removed or are covered by highway fill, and information such as fan slope, area, and volume cannot be collected at these fans. However, morphometric parameters for drainage basins above these fans are easily determined from digital elevation models (DEM)s.

3 METHODS

3.1 *Debris-flow records*

There are 19 fans in the study area with either subsurface exposures of stratigraphy, historic records of flow events, or both (Fig. 1). At each of these fans, we determined the number of debris-flow events that occurred during the period of record, which ranged from 22 years to more than 11,000 years (Table 1). Because we are confident that both types of records are incomplete, the numbers of debris flows that we were able to identify are considered minimums. In the case of the stratigraphic records, many of the fan exposures were from small parts of fans, not complete longitudinal or latitudinal cross-sectional exposures. In the case of historic records, we were only able to compile what was published or observed, which is certainly an incomplete record. Because the numbers of debris flows recorded at each fan are minimums, the mean recurrence intervals calculated from the records are maximums, and the debris-flow probabilities calculated from mean recurrence intervals are thus minimums. In the next two sub-sections we describe how each type of record was developed and compiled.

3.1.1 *Fans with exposed stratigraphy*

There are 13 fans in the study area where fan stratigraphy is exposed (Figs. 1, 3). These fans were distributed throughout the study area (Fig. 1), but most were located either along the south side of the valley below the line of glacial extent, or along the north side of the valley above the line of glacial extent (Fig. 1). At each of these fans, we mapped the exposures in the field and dated the deposits using radiocarbon dating. The exposures generally revealed poorly-sorted sediments, numerous buried A-soil horizons, and sparse to abundant deposits of charcoal (Fig. 3). Because sediments were derived predominantly from metamorphic rocks, they were typically dominated by sand- and gravel-sized material. The A horizons were generally 10 to 20 cm thick and were easily distinguished from the surrounding sediments by their relatively high organic content and dark gray to black color. The A horizons and deposits of charcoal were most common on north-facing fans where solar exposure conditions (shading) created soil conditions that were generally cooler and wetter than on south-facing fans.

At each mapped fan we identified the dominant flow process as either debris flow or water-dominated flow (floods). Deposits were interpreted as having a debris-flow origin if they were matrix supported, poorly sorted, and contained randomly oriented clasts. Deposits were classified as having a flood origin if they were clast supported, were moderate to well sorted, or contained internal stratigraphy. Flow processes were sometimes difficult to interpret because of ambiguous sedimentological characteristics or limited exposures. Also, it was sometimes difficult to determine if adjacent, sedimentologically distinct deposits represented temporally distinct flow events or were part of a continuum of flow processes resulting from a single event. Where there were ambiguities, we relied on buried A horizons and radiocarbon dates to determine the number of debris-flow events at each site. That is, because A-horizons represent clear hiatuses in deposition, we used them to lump deposits together if we lacked other definitive temporal information. Radiocarbon dates also helped to distinguish a few deposits from one another by providing constraints on the timing of the deposits. Using these methods, we determined that 11 of the 13 fans were dominated by debris-flow deposits, one had about equal numbers of debris-flow and flood deposits, and one was dominated by flood deposits (Table 1). We only used data from the debris-flow fans and the mixed fan to estimate mean recurrence intervals and future probabilities of debris-flow events.

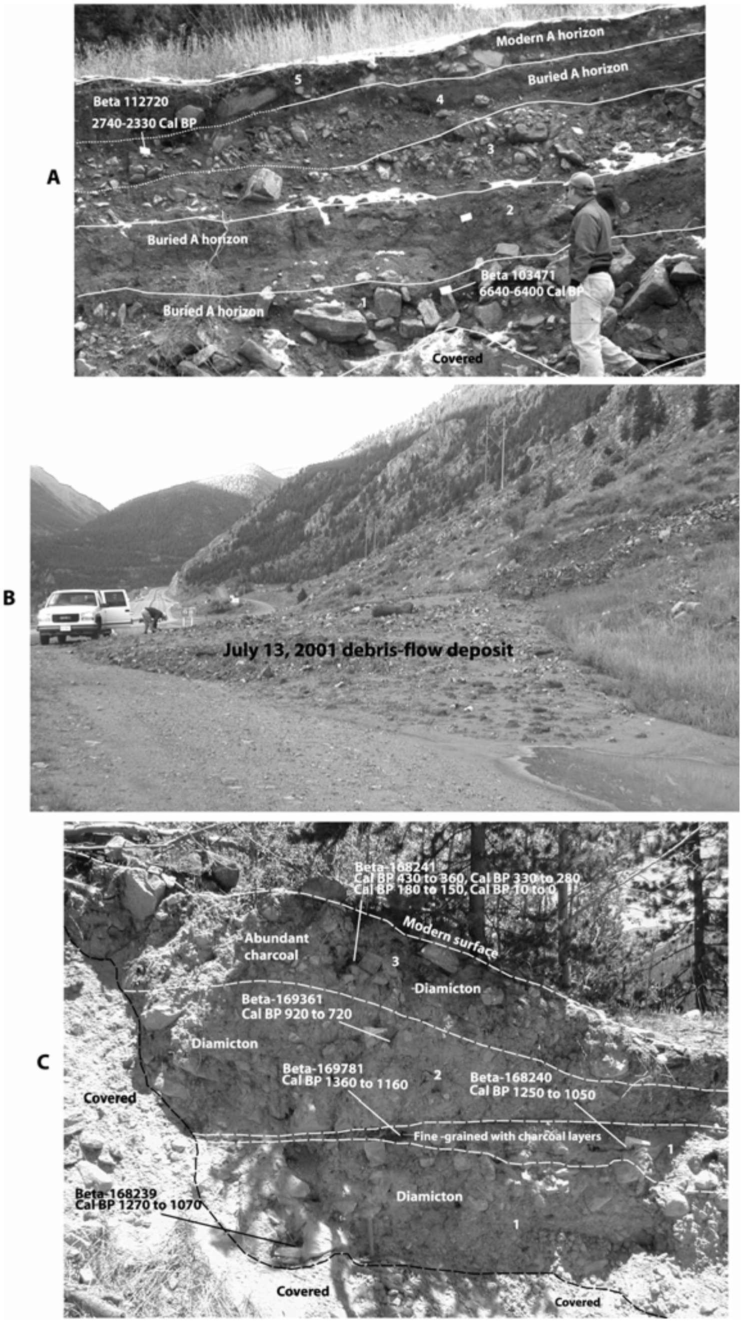

Figure 3. Examples of debris-flow deposits, buried soils, and radiocarbon dates in the study area. Radiocarbon dates are given as calibrated ages with a 2 standard deviation range. A) Exposure at fan 242.0S. B) Debris-flow deposit at fan 228.55N. C) Exposure at fan 219.4N.

Table 1. Data from fans and basins upslope from fans. Periods of record for HS and S fans are intercepts of the oldest radiocarbon age in the exposure with a calibration curve. NA means not applicable.

Fan Number	Type of record; H, historic; S,stratigraphic; HS, both	Melton's number of drainage basin upslope from fan	Period of record (years)	Number of events exposed or recorded	Mean debris flow recurrence interval (years)	Interpretation; F, flood dominated fan; D, debris-flow dominated fan; M, mixture of F and D	Annual probability of debris flow on fan (% chance in any given year)
219.3N	HS	0.479	11,570	4	2893	D	<0.1
219.4N	HS	1.057	1180	3	295	D	0.3
228.1N	S	0.748	3970	2	1985	D	0.1
228.25S	S	0.910	1410	2	705	D	0.1
228.41N	H	1.393	22	3	7	D	13.3
228.55N	H	1.750	22	3	7	D	13.3
230.71N	H	1.486	22	2	11	D	8.7
230.73N	H	1.432	22	2	11	D	8.7
230.76N	H	1.551	22	2	11	D	8.7
233.7N	S	0.914	3795	2	1898	D	0.1
234.6S	S	0.495	6650	4	1663	D	0.1
235.7S	S	0.660	10,560	4	2640	M, 7 events, 3 flood events, 4 debris-flow events	<0.1
237.0S	S	0.359	2370	2	1185	D	0.1
237.8S	S	0.332	285	2	NA	F, 2 flood events	NA
239.95N	H	0.256	22	3	NA	F, 3 flood events	NA
240.8S	S	0.698	3895	2	1948	D	0.1
242.0S	S	0.438	6475	5	1295	D	0.1
243.7S	S	0.460	915	2	458	D	0.2
244.7N	S	0.582	930	2	465	D	0.2

3.1.2 *Fans with historic records*

Eight fans had historic records of flow events (Fig. 1). These records included our own observations of debris flows (compiled since the summer of 1996), as well as newspaper and eyewitness accounts of debris flows. We only recorded events if they deposited material on fans. At each fan, we compiled the data on the types of flows (debris flow or flood), dates of flows, and number of events that occurred during the period of observation (about 22 years, Table 1). At two fans that had both historic and stratigraphic records (Table 1), we combined the data to determine the total number of debris flows. We also determined the dominant type of flow processes using field observations as described in the previous section. Seven of the fans were dominated by debris-flow events and one was dominated by flood events (Table 1).

3.2 *Determination of mean recurrence interval at individual fans*

The mean recurrence interval for each of the 19 fans (Table 1) was calculated by dividing the period of record by the number of debris-flow events that occurred during the period of record (Crovelli 2000). For example, if a fan exposure revealed three debris-flow deposits and the oldest deposit contained charcoal that yielded a date of 900 calibrated years before present, then the fan would have an estimated mean recurrence interval of 300 years (900÷3). In general, this method of calculating mean recurrence intervals is more practical than calculating a mean from recurrence intervals determined by dating each debris-flow event because dateable organic material is not always available and the elapsed time between the last debris-flow event and the present day is often not known.

3.3 *Calculation of future debris-flow probability*

The Poisson probability model (Ross 1972) is often used to model geologic processes that are believed to be mutually independent and occur randomly in time (Keaton 1994, Haneberg 2000, Crovelli 2000). Field observations in the study area indicate that debris-flow events are triggered by intense rainstorms that mobilized material by rilling and fire-hose processes (see discussion section). These observations suggest that debris flows are mutually independent and occur randomly in time.

Following methods described by Crovelli (2000), Coe et al. (2000) and Coe et al. (in press), we consider the occurrence of debris flows during a specified future time in a particular area. In our case, the specified future time is 1 year and the area is that of each fan where mean recurrence interval data have been estimated.

We denote $N(t)$ to be the number of debris flows that occurs during a future time t at each fan. Probability is defined as the probability of one or more debris flows occurring during a specified future time t, that is, $P\{N(t)\geq 1\}$.

For each fan where mean recurrence interval data are available (Table 1), the probability of future debris-flow events was determined using the Poisson probability model, $P\{N(t)\geq 1\} = 1\text{-}e^{-t/\mu}$, where μ is the observed mean recurrence interval, and t is a period of time in the future for which the probability is calculated (e.g., $t = 1$ year for annual probability). The observed mean recurrence interval is used under the assumption that the future occurrence of debris flows will be similar to the past occurrence of debris flows. Formulation of the above form of the Poisson probability model is given in Crovelli (2000).

3.4 *Basin morphometry*

We are limited in the morphometric data that can be measured along the corridor because, as previously stated, some fans have been removed or covered, making it difficult or impossible to measure parameters such as fan slope, fan area, or fan volume. Therefore, we are limited to morphometric parameters that can be measured for the drainage basins above the fans. Fortunately, 30 m Digital Elevation Models are available for the study area, and these data were used to characterize basin morphology. One way to characterize basin morphology is by using Melton's number, which is defined as $H(A)^{-0.5}$, where H is basin height above the fan and A is basin area above the fan (Melton 1965). Melton's number is a measure of basin ruggedness, that is, basins that are small and steep have higher Melton's numbers than basins that are large and have low-to-moderate relief. Investigators who have conducted assessments of debris-flow hazards on fans in different geographic areas (Jackson 1987, Marchi et al. 1993, Parise & Calcaterra 2000) have had success using Melton's number to classify fans according to dominant type of flow (debris flow or flood).

Field observations in the study area (also see discussion section) suggest that basins with relatively low Melton's numbers drain to fans that were predominantly formed by floods, and that basins with relatively high Melton's numbers drain to fans that were predominantly formed by debris flows. Additionally, basins above the glacial limit tend to have higher Melton's numbers than basins below the glacial limit (Coe et al. 1998). For this study, we determined Melton's number for drainage basins upslope from the 19 fans using 30 m DEMs and a geographic information system (Table 1).

4 RESULTS

Mean recurrence intervals at individual fans range from 7 to about 2900 years (Table 1). Annual probabilities for debris-flow events range from 0.1% to about 13% (Table 1). Fans with historic records have the highest probabilities for future events, which raises the question of whether or not the two types of records can be considered a homogenous sample (addressed in the following section). All historic debris flows have occurred along the north side of I-70 above the glacial limit. Unfortunately, there are not enough data available to identify additional patterns in debris-flow activity with respect to the aspect of fans/basins or their positions above or below the maximum extent of glaciation. Melton's numbers for drainage basins above fans range from 0.256 to 1.750 (Table 1). Overall, fans at the mouths of basins with relatively high Melton's have the shortest mean recurrence intervals and fans at the mouths of basins with relatively low Melton's numbers have the longest mean recurrence intervals. This relation is explored in the following section.

5 DISCUSSION

5.1 *Regression analysis of mean recurrence interval and basin morphometry*

We used regression and correlation analysis to define a regression model that relates mean recurrence interval to Melton's number. The model suggests that there is a negative correlation between mean recurrence interval and Melton's number (Fig. 4). That is, fans with the shortest mean recurrence intervals tend to be at basins with the highest Melton's numbers. This relation was modeled using a best-fit exponential equation defined as $y=19{,}400e^{-4.67x}$, where y is mean recurrence interval and x is Melton's number (Fig. 4). With verification through further work, the regression model may be suitable to estimate mean recurrence intervals for fans where there are no stratigraphic or historic records. Further work is needed to verify the model because mean recurrence intervals from both types of debris-flow records (stratigraphic and historic) were used in the regression analysis. Implicit in this approach is the assumption that the two types of records belong to the same sample set. More specifically, the assumptions are that 1) both types of records sample the same rate of debris-flow activity for any given fan, and 2) debris-flow events are treated the same in both types of records, for example, debris-flow events with small volumes would be consistently recorded or not recorded in both types of records. The later assumption seems reasonable because most fans in the corridor are small (<0.5 km^2, Coe et al. 1998). Therefore, small volume events would be treated consistently in either type of record. The first assumption is more difficult to justify given the limited paleoclimatic and historic rainfall data that are available for mountainous parts of Colorado. The first assumption requires that the frequency of debris-flow producing meteorologic events has remained constant throughout the Holocene to present day. Previous work has shown that most historic debris flows in Colorado were triggered by intense (extreme) rainstorms that occurred during the summer monsoon season (Curry 1966, Caine 1976, Menounos 1996, Godt & Coe 2003). The monsoon has been persistent, but of variable intensity, throughout the Holocene in Colorado (Thompson et al. 1993). There is a general consensus from paleoclimatic studies that monsoonal activity was stronger (warmer temperatures and higher summer precipitation) in the early and middle Holocene (prior to about 4 thousand years ago) than in the late Holocene (Markgraf & Scott 1981, Elias 1985, Thompson et al. 1993, Fall 1997). However, the frequency of extreme storms that are most likely to produce debris flows is not known, and cannot be determined from the generally poor temporal resolution of paleoclimatic data.

One possible way to verify that debris-flow frequencies documented by historic records are representative of frequencies documented by stratigraphic records would be by studying subsurface exposures at multiple fans that have had multiple historic debris flows. If these exposures reveal Holocene debris flow recurrence intervals that are similar to historic recurrence intervals, then there would be reasonably strong support for assumption 1. The problem in the I-70 study area is that most fans with multiple historic debris flows do not have subsurface exposures. Such exposures would have to be created by trenching with excavation equipment. The negative correlation between mean recurrence interval and Melton's number could be tested in a different geographic area (e.g., the European Alps) that has a higher rate of debris-flow activity and a longer historic record than the I-70 study area. If such an area were studied, it may be possible to verify the model using only historic data.

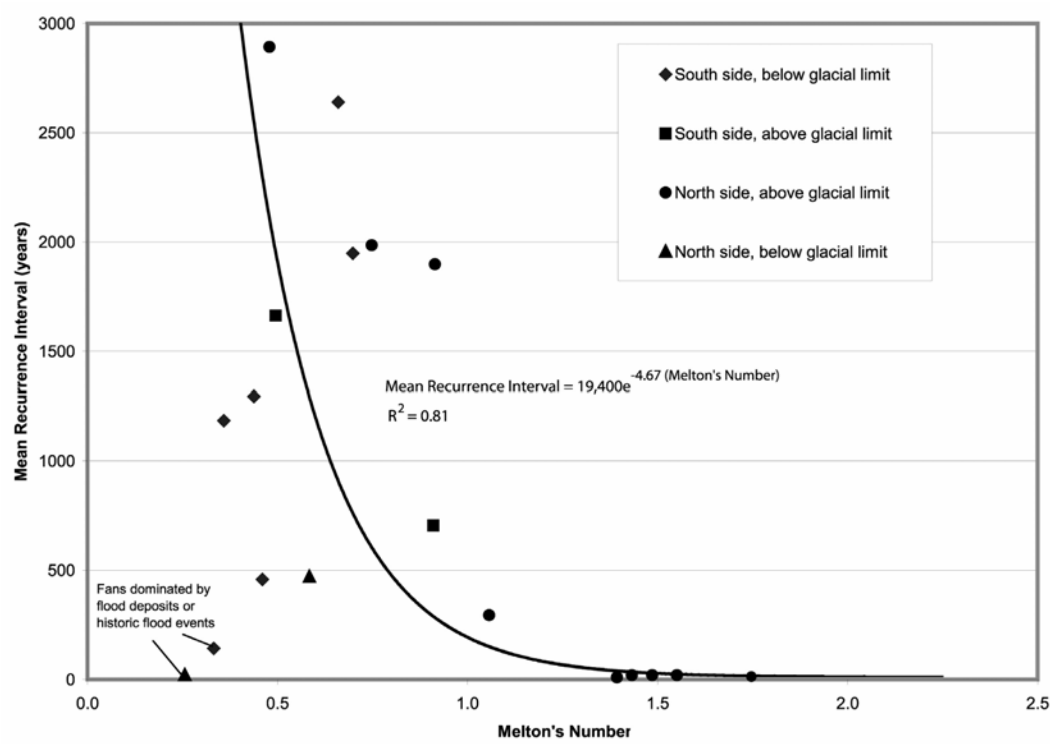

Figure 4. Scatter plot showing mean recurrence interval and Melton's number data from fans in the study area. Best-fit line and equation from regression analysis is shown. Fans dominated by floods were not used in the regression analysis.

5.2 *Field observations*

Our observations of the occurrence of debris flows since the summer of 1996 provide some insight into an understanding of the physical reason(s) for the empirical correlation between basin ruggedness and debris-flow frequency. From 1996 to present (September, 2002), we have observed widespread debris flows once, on July 28, 1999 (Coe et al. 2002, Godt & Coe 2003), and localized debris flows and flooding multiple times. All of the debris flows that we have observed have occurred on fans along the north side of the highway above the glacial limit. Multiple debris flows occurred on fans near Georgetown (fans 228.1N to 230.76N, Table 1, Fig. 1). These fans are at basins that contain loose material and have Melton's numbers greater than 1.3 (e.g., Fig. 2b). Debris flows in these basins initiated by progressive rilling (concentration of overland flow that increases slope-parallel shear stress and mobilizes loose sediment primarily at knickpoints and plunge pools; see Horton 1945, Johnson & Rodine 1984, Cannon et al. 2003) and fire-hose (running water that impacts and mobilizes debris, often from the heads of fans; see Johnson & Rodine 1984) processes, tended to travel short distances (less than 1 km), and contained volumes of material that were generally less than 1,000 m^3 (Fig. 3b). These commonly occurring debris flows were much different from a debris flow that occurred at fan 219.3N (Fig. 1 and 2c, and Table 1) on July 28, 1999 (Coe et al. 2002, Godt & Coe 2003). This debris flow initiated by rilling in a large basin (Melton's number 0.479) at an elevation of about 3,900 m, traveled 2.5 km down a drainage channel, and deposited 26,400 m^3 of bouldery debris on I-70 (Fig. 2c). An analysis of the triggering rainfall and the stratigraphy at fan 219.3N indicated that the July 1999 debris flow was an infrequent event (mean recurrence interval of about 2900 years, Table 1). About 480 other debris flows occurred in the alpine area outside our I-70 study area on July 28, 1999, but most of these deposited materials at the base of hillslopes within basins, not at fans at the mouths of the basins. The debris flow at fan 219.3N was unusual because it flowed to the fan at the mouth of the basin.

These observations suggest that one of the reasons that debris flows occur frequently on fans at the mouths of basins with relatively high Melton's numbers is that they have a greater likelihood of flowing to the fan than do debris flows in basins with relatively low Melton's numbers. We suspect that if debris flows occurred with equal frequency on hillslopes in all basins, many of the debris flows in the large basins would deposit material at the base of hillslopes within the basins, not on fans at the mouth of the basins. This would also explain why fans at basins with very low Melton's numbers (less than about 0.35 in this study, Fig. 4) are dominated by flood events, not debris-flow events. In basins with high Melton's numbers (such as the one seen in Fig. 2b), materials deposited at the base of the hillslope and at the mouth of the basin are essentially the same. Debris flows in these basins simply flow down the hillslopes and are deposited on fans.

Differences in debris-flow initiation processes may also be a factor controlling the frequency of debris flows that flow to fans. All of the debris flows that we observed above line of maximum glaciation on the north side of I-70 were initiated by rilling or fire-hose processes. We do not know what debris-flow processes dominate in basins below the line of glacial extent because there have not been any historic or modern flows. However, because the basins tend to be less rugged (lower Melton's numbers) and generally more covered with trees (especially on the south side of the highway), debris flows that initiate and mobilize from landslides might be more common than the erosive types of initiation processes (rilling and fire hose) that dominate in steep basins mantled by loose debris and little or no vegetation. If the types of initiation process are different, the triggers for the flows (e.g., the amount and intensity of rainfall), which could affect debris-flow frequency, may also be different. Additionally, the presence of charcoal in fan stratigraphy throughout the study area suggests that forest fires may play an important role in controlling debris-flow frequency. Clearly, debris flows are controlled by a complex interplay of factors (e.g., Moscariello 2002) that make their prediction a challenging task.

6 CONCLUSIONS

Stratigraphic and historic records were used to estimate maximum mean recurrence intervals and minimum probabilities for future debris flows on 19 fans along the Interstate 70 highway corridor in Colorado. A regression analysis of mean recurrence interval data and drainage-basin morphometry at the fans yielded the regression model, $y=19{,}400e^{-4.67x}$, where y is mean recurrence in years and x is Melton's number, a dimensionless measure of basin ruggedness derived from a digital elevation model. This regression model may be suitable to estimate mean recurrence intervals on fans with no stratigraphic or historic, but needs to be tested by further work.

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