WATER RESOURCES RESEARCH, VOL. 42, W02410, doi:10.1029/2004WR003778, 2006

Threshold relations in subsurface stormflow: 1. A 147-storm analysis of the Panola hillslope

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Received 1 November 2004; revised 14 August 2005; accepted 26 October 2005; published 21 February 2006.

[1] Subsurface stormflow is a dominant runoff-producing mechanism in many upland environments. While there have been many trench-based experimental studies, most of these investigations have examined only a handful of storms. We analyzed subsurface stormflow in response to 147 rainstorms at a trenched hillslope in the Panola Mountain Research Watershed between February 1996 and May 1998. We used this unique long-term data set to examine how often the hillslope delivers water, the contribution of pipe flow to total flow, and the persistence of spatial patterns of flow at the trench face. The long-term data set showed a clear threshold response of subsurface stormflow to storm total precipitation. For storms smaller than the precipitation threshold of 55 mm, little subsurface stormflow was observed. For events exceeding the threshold, there was an almost 2 orders of magnitude increase in subsurface flow compared to subsurface flow from storms smaller than the threshold. Pipe flow was an important component of total subsurface flow and showed a similar threshold behavior. We observed a linear relation between total pipe flow and total subsurface stormflow. Contributions of different trench segments to total trench flow changed seasonally and with changes in precipitation and antecedent conditions. Our results suggest that the threshold relation at the hillslope scale may be an emergent behavior of combined processes internal to the hillslope and perhaps point the way toward how to characterize hillslope processes. A companion paper (Tromp-van Meerveld and McDonnell, 2006) explores the physical mechanisms responsible for the threshold behavior.

Citation: Tromp-van Meerveld, H. J., and J. J. McDonnell (2006), Threshold relations in subsurface stormflow: 1. A 147-storm analysis of the Panola hillslope, *Water Resour. Res.*, *42*, W02410, doi:10.1029/2004WR003778.

1. Introduction

[2] Excavations at experimental hillslopes have been a common method for quantifying subsurface stormflow and water mixing in response to storm rainfall and snowmelt. Hillslope trench analyses of subsurface stormflow date back to the 1940s with an explosion of such investigations in the 1960s (for reviews, see *Kirkby* [1978] and *Bonell* [1993, 1998]). Early studies focused mainly on the temporal dynamics of throughflow and often used small (<1 m wide) trenches [*Atkinson*, 1978]. Some common and important observations have included (1) the influence of soil horizon contacts in generating lateral subsurface stormflow [*Whipkey*, 1965; *Mosley*, 1979], (2) saturated wedge development and growth from the trench face upslope [*Dunne and Black*, 1970; *Weyman*, 1973], (3) the importance of lateral soil pipes in fast delivery of water and the rapid response of subsurface flow [*Mosley*, 1982; *Tsuboyama et al.*, 1994], and (4) preevent water dominating subsurface stormflow even when pipe flow appeared to dominate total flow at the trench [*Hewlett and Hibbert*, 1963; *Sklash et al.*, 1986; *McDonnell*, 1990; *Anderson et al.*, 1997]. In fact, lateral pipe flow of chemically dilute [*Burns et al.*, 1998] preevent water [*Sklash et al.*, 1996; *Peters et al.*, 1995; *Uchida et al.*, 1999] emanating from study trench faces has been a common observation.

[3] Notwithstanding these important observations, our ability to develop simple rules of spatial and temporal hillslope behavior has been minimal. For development of general rules for spatial behavior, a major impediment has been the size of the trench excavations to date. With a few exceptions, most trench excavations have been very narrow (1–5 m). *Woods and Rowe* [1996] created a 60 m long trench at the Maimai, New Zealand, hillslope to analyze the spatial patterns of subsurface stormflow and transport in relation to the surface and subsurface topography. Using this whole-slope-based excavation approach, *Woods and Rowe* [1996] showed the large effect of antecedent wetness (quantified using an antecedent precipitation index) and storm size on the lateral distribution of subsurface stormflow at the Maimai hillslope, New Zealand. Work at the trenched experimental hillslope at the Panola Mountain Research Watershed (PMRW) in Georgia, United States (the site of the investigation discussed in this paper), by *McDonnell et al.* [1996] and *Freer et al.* [1997, 2002] showed for three rainstorms that flow at the trench face was highly correlated with the upslope contributing area defined by the bedrock topography

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(rather than the often-assumed surface topography derived contributing area). The spatial pattern of the bedrock topographic index as a control on lateral subsurface stormflow patterns was also observed by *Peters et al.* [1995] at the Plastic Lake hillslope in Ontario, Canada, by *Tani* [1997] at the Minamitani hillslope on Honsyu Island, Japan, by *McDonnell et al.* [1998] at the Maimai hillslope, and by *Hutchinson and Moore* [2000] at a hillslope in British Columbia, Canada.

[4] While some rules are now emerging for spatial behavior of hillslope runoff response, few studies have examined the persistence of the spatial response and how input maps to output during different storm amounts, intensities and durations. Even at the intensively studied trenched hillslope sites, we rarely have more than a handful of storms to work with because of the extreme difficulty and cost of obtaining the data and maintaining the infrastructure. We lack good data for development of simple rules for hillslope response. While there have certainly been indications from past studies that outputs do not appear to be proportional to the inputs across all storm amounts, and intensities, we do not have enough storms recorded at any given site to quantify these possible relations. Moreover, the stability of the observed spatial patterns across seasons, or with changes in precipitation and antecedent moisture conditions has rarely been assessed.

[5] This paper presents analyses of subsurface stormflow at the Panola Mountain Research Watershed trench face from 147 rainstorms between February 1996 and May 1998. This large number of rainstorms allows exploration of hillslope behavior and questions regarding to the persistence of spatial patterns in subsurface stormflow. Here we address the following questions: (1) How often does the hillslope deliver water laterally to the slope base and therefore to riparian zones and stream banks? (2) What is the contribution of lateral pipe flow to total flow at the trench face? (3) Does total trench flow and its subcomponents of matrix flow and lateral pipe flow increase linearly with storm size? (4) How persistent are the spatial patterns of subsurface stormflow at the trench face across seasons, soil moisture conditions, and storm characteristics?

2. Study Site

[6] The Panola Mountain Research Watershed (PMRW) is located about 25 km southeast of Atlanta, Georgia, USA, in the southern Piedmont. The forested watershed is dominated by hickory, oak, tulip poplar, and loblolly pine [*Carter*, 1978]. The 10 ha western upper catchment at Panola (within which the study hillslope is located) is underlain by the Panola Granite, which is a biotite-oligoclase-quartz-microcline granodiorite [*Crawford et al.*, 1999].

[7] The study hillslope is located on a southeast facing slope and has a slope of 13°. The lower boundary of the study hillslope is located 30 m upslope from an ephemeral stream and is formed by a 20 m wide trench. The upper boundary of the study hillslope is formed by a small bedrock outcrop. Soil depths on the study hillslope range from 0 to 1.86 m and average 0.63 m. The surface topography of the study hillslope is planar while the bedrock topography is very irregular; resulting in highly variable soil depth across the study hillslope (Figure 1a). The soil on the study hillslope is a light colored sandy loam without clear structuring or layering, except for a ~0.15 m deep organic-rich soil horizon. The soil is classified as the coarse, loamy, mixed thermic Typic Dystrochrepts from the Ashlar series. There are no observable differences in soil type across the study hillslope. We found a coarser more saprolitic layer under this soil profile only in the area of very deep soils (located 17–22 m upslope from the trench face). The thickness of the saprolitic layer was 0.15–0.35 m.

[8] The climate is humid and subtropical with a mean annual air temperature of 16.3°C and mean annual precipitation of 1240 mm, spread uniformly over the year [*NOAA*, 1991]. Rainfall tends to be of long duration and low intensity in winter, when it is associated with the passage of fronts, and of short duration but high intensity in summer, when it is associated with thunderstorms. The dryness index (annual potential evaporation/annual precipitation) of the study site is 1.3, when the potential evaporation is calculated using the Hargreaves equation [*Hargreaves*, 1975]. Streamflow at PMRW has a strong seasonal pattern; the highest baseflows occur during the dormant season (November through April), and the lowest occur during the growing season (May through October). Annual stream yield from the 41 ha catchment varied from 16 to 50% of precipitation during 1986–2001 [*Peters et al.*, 2003]. Overland flow is uncommon on the forested hillslopes and was observed only during very intense thunderstorms after extended dry periods. Even during these storms, overland flow was restricted to small areas and reinfiltrated within several meters.

3. Methods

[9] A 20 m long trench was excavated down to competent bedrock in 1995. The trench was divided into ten sections and discharge from each section and from five individual soil pipes was measured by routing the flow through tipping bucket gauges. The soil pipes were developed form decayed roots. We define the total lateral flow from these five individually plumbed pipes as pipe flow and flow from the remaining sections as matrix flow. It should be noted that a portion of the matrix flow actually comes from several smaller preferential flow paths within the soil profile and particularly at the soil-bedrock interface, which were not individually plumbed. Total flow at the trench face is defined as the sum of pipe flow and matrix flow. For this analysis, the individual trench sections were regrouped into 4 m sections based on similar subsurface stormflow and topographic characteristics. Figure 1b shows a front view of the trench face including the location of five individually plumbed soil pipes. When total flow for a 4 m section was calculated, flow from a pipe in that section was added to the measured matrix flow from the 4 m section. When a pipe was located on the border of two sections (M8, see Figure 1b), flow from that pipe was partitioned equally between the two adjacent sections. Additional details of the trench and the flow collection system and early results are described by *McDonnell et al.* [1996], *Freer et al.* [1997, 2002], and *Burns et al.* [1998].

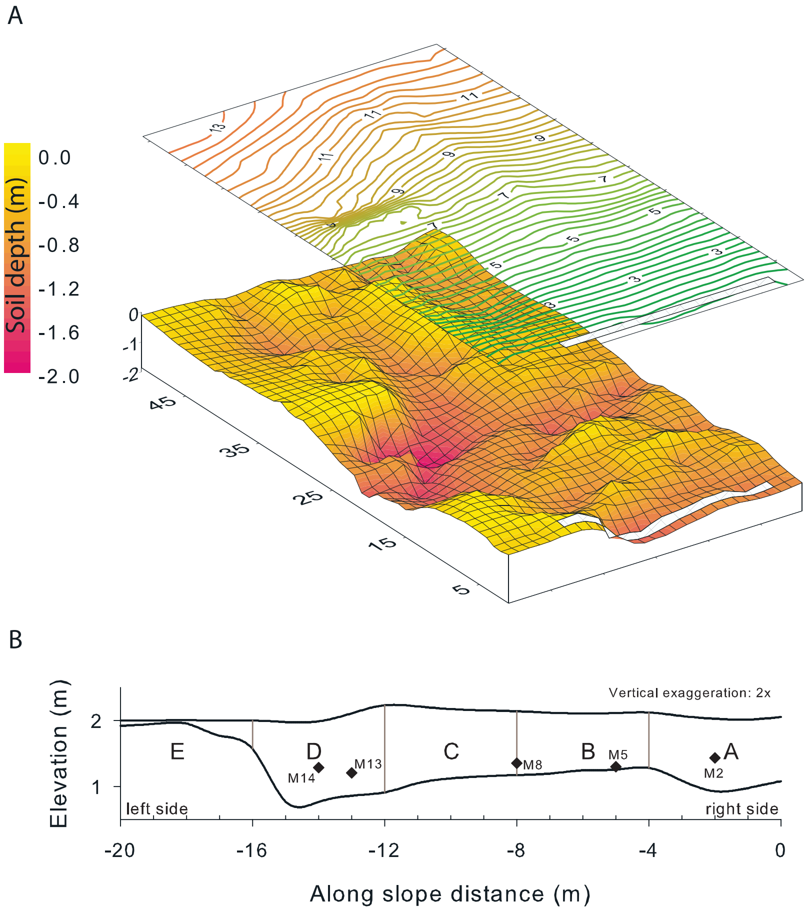

Figure 1. Map of the Panola hillslope showing (a) the surface and bedrock topography and soil depth and (b) a front view of the trench face with the location of the 4 m wide trench sections and the individually plumbed soil pipes (black diamonds). The shaded area in Figure 1a represents the location of the trench.

[10] In this study, we examine two years of subsurface flow data: from 19 February 1996 to 10 May 1998. This period contained 147 rainstorms (Table 1). The start of a storm was defined as a rainstorm that produced the following streamflow characteristics at the 41 ha gauging station that our hillslope ultimately drained into: a 0.4 L/s rise in discharge within 3 hours or a 30% rise in discharge within 3 hours. For calculation of storm total precipitation, the end of the storm was determined when streamflow reached either 10% of the difference between the streamflow maximum and preevent streamflow or a baseflow level of 5 L/s. For the calculation of subsurface stormflow (total flow, matrix flow and pipe flow at each trench section) the end of the storm was defined as the start of the next storm using the criteria above.

[11] We acknowledge that it is possible that there was a small "under catch" of subsurface flow or a change in timing of measured subsurface flow at the end of the analyzed two year period due to possible trench degradation. We assume that this did not have a large influence on the analysis of the number of subsurface flow-producing rainstorms, the total volume of subsurface stormflow nor the distribution of subsurface flow across the trench. To test this assumption we examined data from each individual calendar year. We found no systematic changes in the distribution of subsurface flow across the trench or

Table 1. Overview of the Characteristics of the Storms Analyzed in This Study

	Number of Storms	Average Storm Size, mm	Median Storm Size, mm	Average Runoff Coefficient, %	Number of Storms With Measurable Subsurface Flow	Number of Storms With > 1 mm Subsurface Flow	Number of Storms With Runoff Coefficient >10%
Total	147	19.9	12.2	5.0	115	9	8
Fall	28	22.0	13.5	5.7	24	2	2
Winter	42	25.6	17.3	9.8	42	6	6
Spring	45	15.7	7.9	0.8	28	1	0
Summer	32	16.6	9.7	0.04	21	0	0

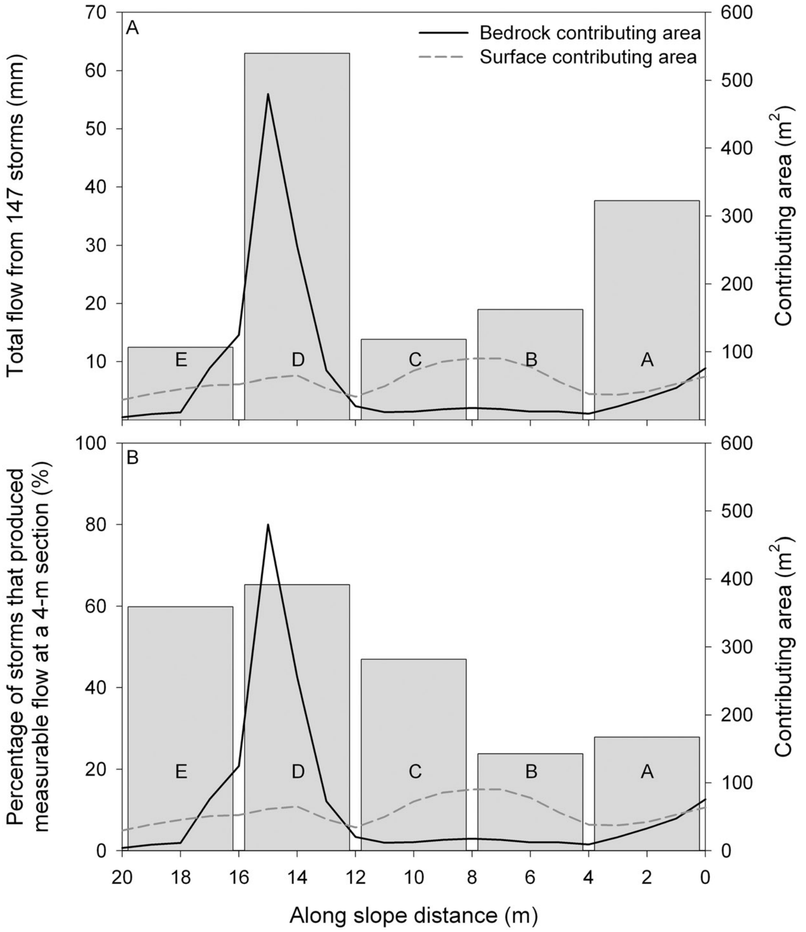

Figure 2. (a) Total subsurface stormflow and (b) the number of storms producing measurable subsurface flow for each 4 m section of the trench. For the location of the trench sections, see Figure 1b.

differences in the volume or ratios of subsurface flow to storm rainfall.

[12] Precipitation was recorded at three locations in the Panola watershed using tipping bucket rain gauges, continuously using a weighing bucket gauge in a clearing, and each week using several Tenite gauges. The tipping bucket rainfall data series were compared to the weighing bucket gauge and the Tenite gauges and combined to yield one rainfall time series. This combined rainfall series was used in this study.

[13] Volumetric soil moisture was measured at a nearby, south facing hillslope from pairs of 0.50 m long, 0.05 m parallel spaced, time domain reflectometry (TDR) probes. The TDR probes were inserted parallel to the slope at 0.15, 0.40, and 0.70 m below the soil surface. These long-term soil moisture measurements are described in more detail by *Peters et al.* [2003].

[14] The hillslope was surveyed on a 2 m grid. Depth to bedrock was measured on the same survey grid network using a 25.4 mm soil corer forced vertically through the soil profile to refusal (=refusal to penetration with the hand held soil corer or auger). A small hand auger was used when soil depth was greater than 1.25 m. The multidirectional flow algorithm of *Quinn et al.* [1991] was used to calculate the contributing area for both the bedrock surface and the soil surface. The contributing area (i.e., upslope contributing area (a)) and topographic index (ln (a/tan β), where β is the local slope angle [*Kirkby*, 1975]) were calculated for both the surface topography and bedrock topography [*Freer et al.*, 1997].

4. Results

4.1. Total Volume and Number of Storms Producing Subsurface Stormflow

[15] Analysis of rainfall and subsurface stormflow indicates that 22% of the rainstorms did not produce any measurable flow at the trench face. Most of the rainstorms (94%) did not produce significant flow at the trench face, defined as more than 1 mm total measured subsurface flow (Table 1). For most rainstorms (90%), the runoff coefficient was less than 1%. Total subsurface flow produced by all of the 147 rainstorms was only 5% of total precipitation. The maximum runoff coefficient for an individual storm was 27%. The runoff coefficient was more than 10% for only eight of the 147 rainstorms (Table 1). There was a strong seasonality in the runoff coefficient. The seasonal averages varied from 5.7% to 9.8% to 0.8% to 0.04% for fall, winter, spring and summer, respectively. Seasonality in streamflow runoff coefficients at Panola was reported by *Peters et al.* [2003].

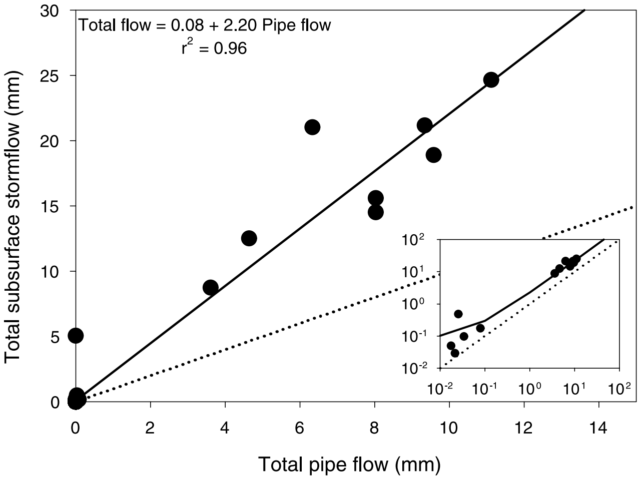

Figure 3. The relationship between storm total pipe flow and storm total subsurface stormflow at the trench face. The insert shows the relation on a log-log scale to show the smaller volumes. The solid line represents the regression line, and the dotted line represents the 1:1 line.

[16] The second 4 m section from the left side (looking upslope) of the trench (section D, 12–16 m along slope distance), which had the largest contributing drainage area based on the bedrock topography, produced more subsurface flow and more frequent subsurface flow than the other sections of the trench (Figure 2). Subsurface flow was highest at this 4 m section for 61% of the rainstorms that produced any measurable subsurface stormflow. These multistorm results are consistent with the individual storm results of *McDonnell et al.* [1996] and *Freer et al.* [1997, 2002] who showed for three winter storms in 1996 that the trench section with the largest bedrock contributing area produced most of the subsurface stormflow. These multistorm results also support, indirectly, the flushing frequency hypothesis of *Burns et al.* [1998], which states that subsurface stormflow is produced more often from the left side of the trench than from the right side of the trench, leading to greater leaching of base cations from the left side of the trench.

4.2. Role of Pipe Flow

[17] Pipe flow contributed significantly to total flow at the trench during the study period. Of the total measured trench flow during the 147 rainstorms, 42% came from the five individually plumbed soil pipes. One large pipe (M14), located in the section with the high bedrock contributing area (section D) and 0.70 m below the soil surface (see Figure 1b), delivered 25% of all measured subsurface flow during the study period. For the 147 rainstorms, there was a very strong linear relation ($r^2 = 0.96$) between storm total subsurface flow and storm total pipe flow (Figure 3), suggesting a similar mechanism for the initiation of both matrix flow and pipe flow [see *Uchida et al.*, 2002].

[18] Pipe flow was a large contributor to total subsurface flow at the trench during winter periods and during a large (153 mm) rainfall event in the fall of 1997. Pipe flow was not important during the rainstorms in summer and spring except for a few very small subsurface flow-producing rainstorms. Pipe flow accounted for 50% of total subsurface flow during fall, 41% during winter, 0% during spring and 2% during summer. During individual rainstorms pipe flow ranged from 0 to 100% of the total measured flow and represented a high percentage of total flow during wet conditions and very dry conditions (as defined by the TDR readings on the nearby hillslope at 0.70 m depth (Figure 4a)). This relation was less clear for soil moisture measured at 0.15 m depth (Figure 4b). It should be noted that during very dry conditions, when the percentage of pipe flow to total flow was large, total subsurface flow (and thus also total pipe flow) was very small. The percentage of pipe flow to total flow did not correlate with total rainfall, the maximum 5 min rainfall intensity or the maximum 1 hour rainfall intensity.

[19] The relative importance of the five individually plumbed soil pipes to total pipe flow varied seasonally (Figure 5). Pipe M14 was the most important soil pipe in terms of total pipe flow production during winter and spring, when pipe flow was large. Pipe M2, located in section A, 2 m from the right side of the trench at 0.59 m depth below the soil surface (see Figure 1b), was the only soil pipe that flowed during very

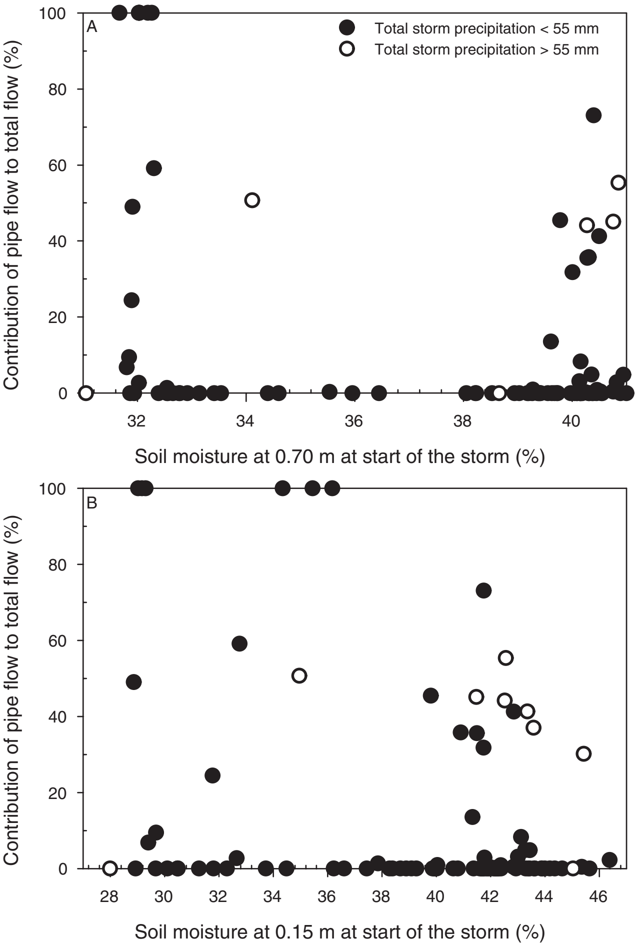

Figure 4. The relationship between the contribution of pipe flow to total flow and the soil moisture readings (a) at 0.70 m and (b) at 0.15 m below the soil surface at the start of a storm.

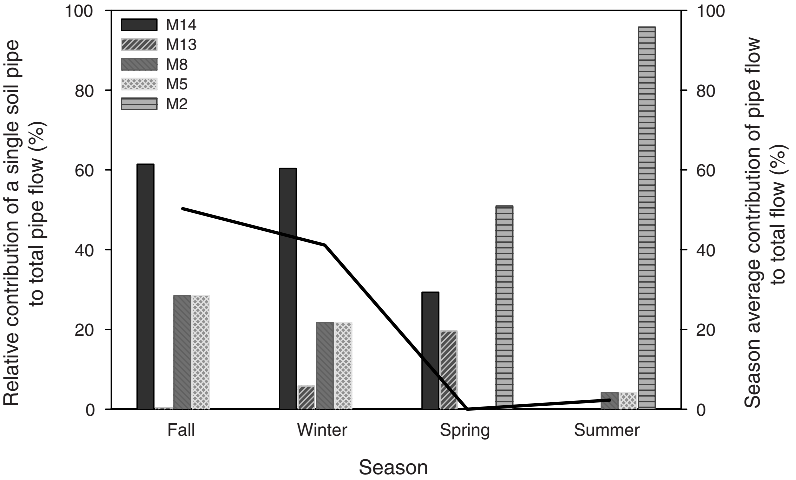

Figure 5. Seasonality in the relative importance of the individual soil pipes to total pipe flow (bars) and the seasonal average contribution of pipe flow (from the five individually plumbed soil pipes) to total subsurface flow (line). For the location of the individually plumbed soil pipes, see Figure 1b.

dry conditions, when total pipe flow and total flow were small.

4.3. Threshold Response of Subsurface Stormflow

[20] Our analyses suggest that there is a clear threshold for significant (>1 mm) subsurface stormflow to occur; significant subsurface stormflow occurred only during rainstorms larger than 55 mm (Figure 6). For storms larger than this threshold, there was an almost 2 orders of magnitude increase in subsurface flow compared to subsurface flow from storms smaller than this threshold. This precipitation threshold was similar for total flow, matrix flow and pipe flow (Figure 6). Even within our large data set, there were not enough very large rainstorms under dry conditions that produced significant subsurface stormflow to determine if a threshold exists (and what its value would be), to determine if the subsurface flow response continued to be linear with increasing total rainfall or if there is yet-unobserved behavior for these exceptionally large events with dry antecedent moisture conditions. Figure 7 shows that both antecedent moisture conditions at depth and total precipitation amount determine whether or not significant flow (>1 mm) occurs. Figure 7 shows that soil moisture content at the start of the storm and total precipitation form three "zones" with respect to the depth of total subsurface stormflow (no measurable flow, <1 mm, and >1 mm total subsurface flow). However, we acknowledge that the boundary between "no measurable flow" and "less than 1 mm total flow" is not very sharp. Total flow, total matrix flow, and total pipe flow did not correlate with the 5 min or 1 hour maximum rainfall intensity.

[21] To test how well defined the precipitation threshold is, we calculated the sum of the squared deviations from an assumed step function for each measured precipitation depth. The threshold was quantitatively defined by the following procedure. The observations were split in two groups defined by a possible threshold in precipitation depth. For each group below and above the possible threshold, the sum of squared deviations of subsurface flow from the average of each group was calculated and added:

$$R(p_t) = \sum \left(S(p < p_t) - \overline{S(p < p_t)} \right)^2 + \sum \left(S(p > p_t) - \overline{S(p > p_t)} \right)^2$$

where p_t is the possible precipitation threshold, p is the storm total precipitation, S is the observed storm total subsurface flow for a storm of size p, and $R(p_t)$ is the sum of the squared deviations for a threshold at p_t. This procedure was repeated for all possible precipitation thresholds between 0 and 100 mm. The calculated threshold was then defined as the precipitation value where the sum of the squared deviations ($R(p_t)$) was minimal. We found that for the 147 storms the threshold was very well defined. We then randomly selected subsets from the 147-storm data set and determined the threshold (i.e., the minimum of $R(p_t)$) for that subset of data. This was done 1000 times for each subset size. The cumulative probability distributions of the calculated thresholds were then calculated (Figure 8). The threshold was well defined as long as the data set was relatively large (90% of the total data set) but became less well defined for smaller subsets. However, even for the smaller subsets there would be a high probability that the precipitation threshold was between 40 and 60 mm.

4.4. Distribution of Flow Across the Trench Face

[22] *McDonnell et al.* [1996] and *Freer et al.* [1997, 2002] have shown for three rainstorms in 1996 that the topography of the bedrock surface is an important control on subsurface stormflow. Analysis of the 147 rainstorms in this study generally confirms this but also shows that the distribution of total flow across the trench face is highly dependent on storm total rainfall and antecedent moisture conditions. Subsurface flow became more uniform across the trench as total subsurface stormflow increased, i.e., with increasing storm size, wetter antecedent conditions and during winter months (Figure 9). During small, low-runoff-producing rainstorms, subsurface flow was concentrated in sections D and E, the section with high bedrock contributing area and

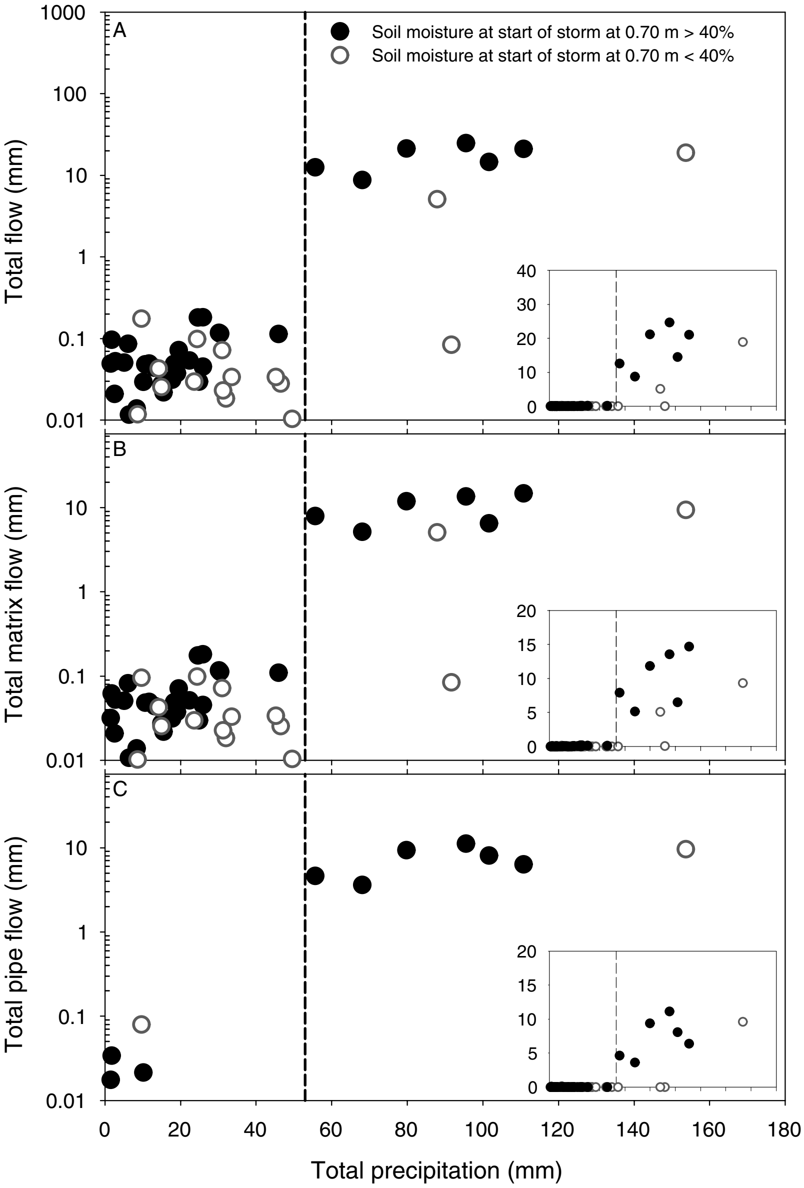

Figure 6. The threshold relationship between storm total precipitation and (a) total flow, (b) total matrix flow, and (c) total pipe flow. The inserts show the same plots on a linear-linear scale. The dashed line represents the precipitation threshold.

the section underlain by shallow soils, respectively (see Figure 1b). With increasing precipitation, antecedent soil moisture content, and total subsurface stormflow, the relative contribution of section E (shallow soils) decreased and the contribution of the other sections (A, B and C) increased. In the extreme during very large rainstorms, most of the flow did not occur in section D (the highest bedrock contributing area section) but occurred in section A, which is a section with a slightly higher bedrock contributing area compared to the trench average. During the summer months almost all flow (90%) came from section E (the section with the thinnest soils, where the bedrock is very close to the surface).

5. Discussion

[23] The Panola hillslope, like many research hillslopes around the world, shows a highly complex set of behaviors in terms of its response to rainfall events. Previous studies at the site have shown how bedrock topography controls the movement of mobile subsurface stormflow laterally down the hillslope [*Freer et al.*, 2002], how base cation concentrations in subsurface stormflow are lower at the slope base where seepage is concentrated [*Burns et al.*, 1998] and how water movement vertically through the soil [*McIntosh et al.*, 1999] and laterally downslope [*McDonnell et al.*, 1996] is dominated by preferential flowpaths. However, all of these previous studies have belied the fact that response from event to event was always somewhat different. This different behavior, even at one well-studied hillslope, was always a limitation to using the Panola hillslope observations to say anything generalizable about hillslope behavior, let alone, use it to explain the response of adjacent ungauged hillslopes.

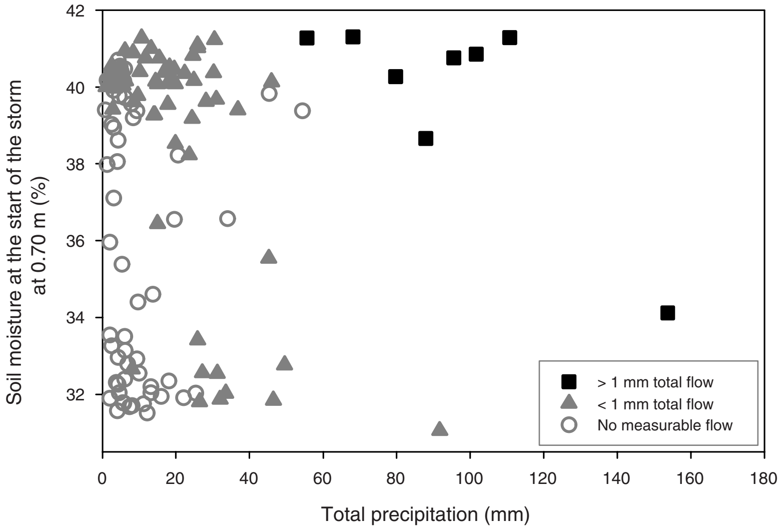

Figure 7. The relationship between storm total precipitation, volumetric soil moisture content at 0.70 m depth at the start of a storm, and storm total subsurface flow.

5.1. Threshold Effects Elsewhere

[24] Our analysis of the 147 storms in this study (including those few storms used as the basis for the papers cited above) showed a clear and unequivocal threshold in the hillslope rainfall-subsurface stormflow relation. We show how these thresholds influence the initiation of subsurface stormflow and how matrix flow and lateral pipe flow show similar threshold behavior (Figure 6). Reexamining earlier hillslope literature, and examining figures and tables from these studies and plotting these rainfall data versus hillslope flow data suggests that thresholds for subsurface flow generation have been observed in the past but have not always been explicitly mentioned. For example, *Whipkey* [1965] showed a relation between total flow and precipitation for dry and wet conditions in his early trench flow studies in the northeast United States. A rainfall threshold of about 35 mm during dry conditions can be inferred from his data [*Whipkey*, 1965, Figure 2, p. 79], but a threshold is not evident during wet conditions. A plot of quickflow volumes against total precipitation from *Mosley* [1979] for the Maimai catchment suggests a rainfall threshold of about 23 mm is necessary to initiate subsurface stormflow. We base this on his data in Table 1 [*Mosley*, 1979, p. 798]; however, we should acknowledge that there is insufficient data to fully demonstrate this threshold and the data could suggest an exponential relation as well. More recently, *Peters et al.* [1995] showed a rainfall threshold of 8 and 17 mm to produce a hillslope and stream response at their Plastic Lake catchment in Canada. *Tani* [1997] showed a clear threshold response from a 6 m wide trench at the base of a slope in Japan. He found a precipitation

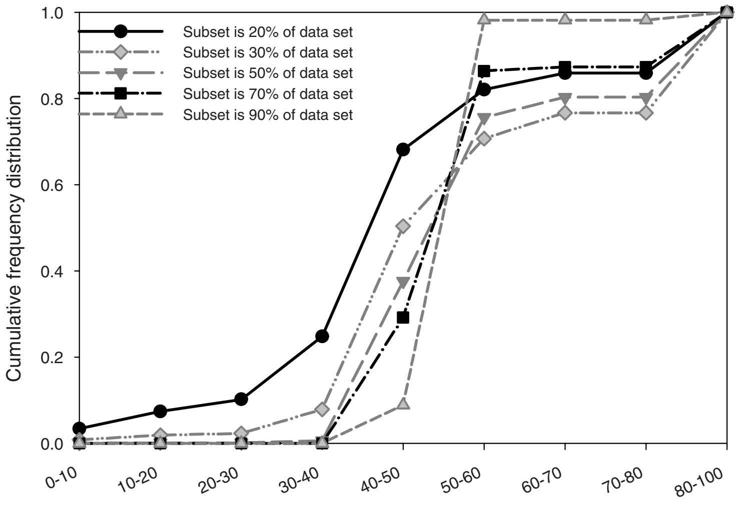

Figure 8. Cumulative frequency distribution of the calculated threshold (i.e., the minimum of the sum of the squared deviations ($R(p_t)$)) for different subsets of the 147-storm data set.

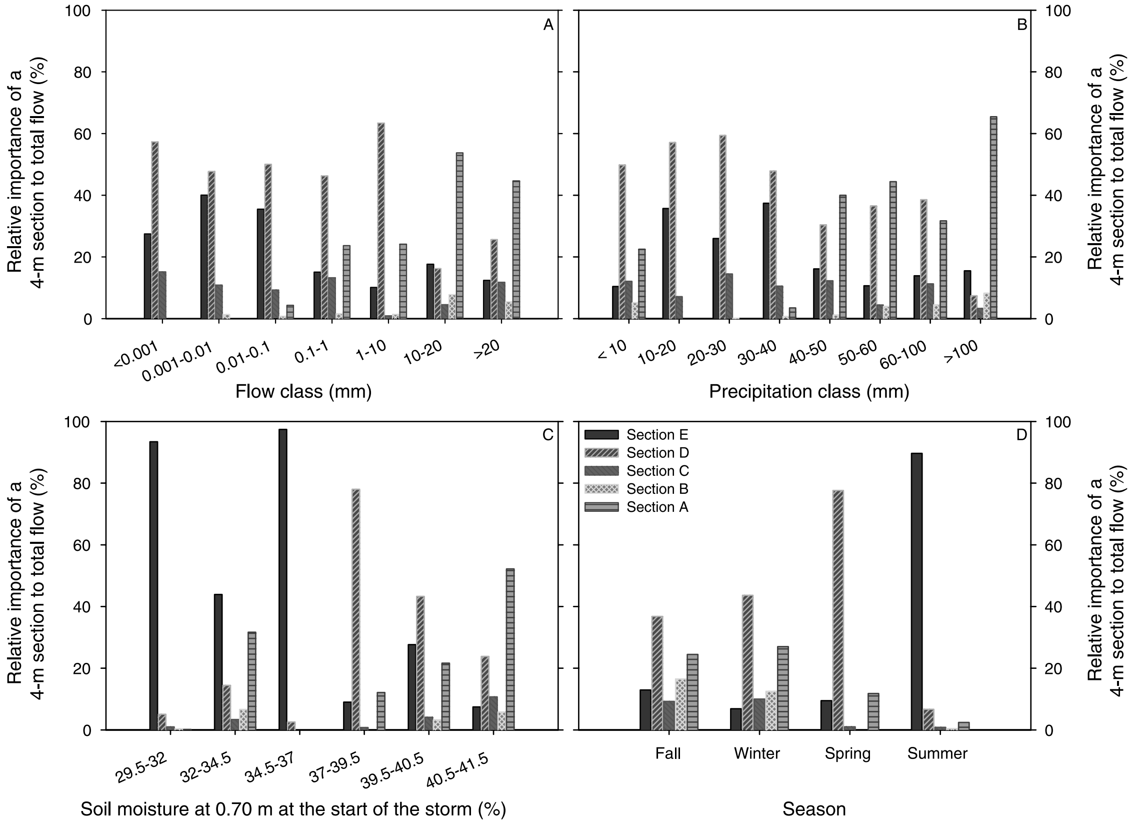

Figure 9. The distribution of subsurface flow across the trench face with (a) increasing total flow, (b) increasing storm total precipitation, and (c) antecedent moisture conditions and (d) for the different seasons. For the location of the trench sections, see Figure 1b.

threshold dependent on antecedent soil moisture conditions. The data from *Tani* [1997, Figure 5, p. 91] indicates that trench flow occurs for rainstorms greater than about 20 mm. After the threshold was reached there was an almost 1:1 relation between precipitation above the threshold and flow from the trench. This was not observed in the data from Panola where for rainstorms larger than 55 mm, the trench flow runoff coefficient ranged from 30% to 80% of precipitation above the threshold. The largest runoff coefficients after the precipitation threshold occurred for the storms with the highest 5 min maximum precipitation intensities. A precipitation threshold response for pipe flow was also apparent in data from other studies; however, these studies often do not mention this threshold response. *Guebert and Gardner* [2001] show a threshold between 10 and 20 mm of precipitation for pipe flow initiation at their upper pit. *Noguchi et al.* [2001] show a threshold-based response function of storm total precipitation for some pipes. However they mention that for wet conditions only small precipitation inputs are needed to initiate hydrologic response. Our work at Panola shows that the threshold for matrix and pipe flow is large even under relatively wet conditions. Consideration of this body of work suggests that the precipitation thresholds for subsurface stormflow and pipe flow generation are not limited to the Panola hillslope and may be a wide spread phenomena, even if not explicitly acknowledged in previous work. It also suggests that there are site specific differences in the threshold amount and the runoff ratio after the precipitation threshold.

5.2. Implications for How We View the Role of Hillslopes in the Hydrology of the Panola Watershed

[25] The runoff coefficient was greater than 10% for only eight of the 147 rainstorms. This confirms the limited role of hillslopes in direct streamflow generation in the Panola watershed that was inferred from the hydrochemical and hydrometric analysis by *Peters and Ratcliffe* [1998] and geochemical analysis by *Hooper et al.* [1998] and *Burns et al.* [2001]. The observed threshold behavior can explain why the hillslopes appear disconnected from the stream or the riparian zone most of the time. Analysis of meteorological data of a 12 year period (1987–1998) reveals that there were 51 rainstorms larger than 55 mm (using the same classification parameters to define the 147 rainstorms in this study). This represents an average of 4.3 rainstorms per year where hillslopes might be able to contribute water and solutes to the channel. Significant flow at the trench did not occur during the summer. During the 1987–1998 period, 38 rainstorms larger than 55 mm occurred during fall, winter and spring, which averages 3.2 rainstorms per year. Only 17 of these rainstorms occurred in the winter when the watershed is generally wettest and trench flow runoff coefficients are the highest. This corresponds to an average of 1.4 rainstorms per year. This analysis shows that in the Panola watershed subsurface stormflow from the

hillslope does not contribute to streamflow during most of the year because only a few rainstorms per year are large enough (larger than the threshold) to produce significant subsurface stormflow on the hillslopes.

5.3. Pipe Flow Thresholds

[26] Matrix flow and pipe flow had very similar precipitation thresholds for initiation of significant flow at the trench (Figure 6). This, combined with the good linear relation between total flow and total pipe flow (Figure 3), could suggest that a similar mechanism is responsible for the initiation of lateral matrix flow and lateral pipe flow [*Uchida et al.*, 2002]. A companion paper [*Tromp-van Meerveld and McDonnell*, 2006] shows that this mechanism relates to (storm event) transient water table development at the soil-bedrock interface (as described by *McDonnell* [1990]). The threshold then relates functionally to the depth of water necessary to exceed storage on the hillslope and the deviation of the slope of the relation between subsurface stormflow and precipitation after the threshold (i.e., the runoff ratio after the threshold) from 1 then represents losses to bedrock or other losses. Once ponding at the soil-bedrock interface occurred, saturated flow followed the bedrock topography, resulting in a spatial subsurface stormflow distribution at the trench face that correlated to the bedrock contributing area [*Freer et al.*, 2002]. Lateral pipe flow occurred only when soil moisture conditions at depth were either very dry or wet. Only one pipe delivered flow during rainstorms with dry antecedent conditions. We hypothesize that during dry conditions, a water table did not develop, and thus total subsurface flow was minimal (less than 0.1 mm). Nevertheless cracking of the soils combined with possibly seasonal hydrophobic soil surfaces during prolonged drought periods [*Peters et al.*, 2001, 2003] could have allowed for rapid delivery to depth and, it would appear, to pipe M2, which delivered all of the trench-scale pipe flow during the summer rainstorms.

5.4. Changing Spatial Patterns of Flow Contributions With Different Storms

[27] The differences in the relative contributions of different parts of the trench face to total flow with changes in total precipitation, antecedent wetness and seasons suggests that the bedrock topography might not be the dominant control on subsurface flow during all rainstorms (as was suggested by the analysis of only a few rainstorms by *McDonnell et al.* [1996] and *Freer et al.* [1997, 2002]). Our multistorm analysis suggests that soil depth controls subsurface flow during small rainstorms with dry antecedent soil moisture conditions. This results in most subsurface flow emanating from section E, during dry conditions. Because this section has a limited contributing area, this section becomes a less important contributor to total subsurface stormflow during larger storms or storms with wetter antecedent conditions. Soil depth and bedrock topography together control subsurface flow during small rainstorms with wet antecedent conditions and the bedrock topography appears to be the primary control during medium to large rainstorms. The 147-storm data set shows another control for very large rainstorms: the production of increased flow from section A (Figure 9), an area with higher-than-average bedrock contributing area but not the highest bedrock contributing area. The reasons for this shift to dominance of section A are subject for further research. Because overland flow occurs rarely, is limited in its spatial extent and the surface topography is planer, the spatial patterns of flow measured at the trench are not due to overland flow patterns (directly, or due to spatial patterns of infiltration of overland flow water). The shift in dominant areas of flow with increasing antecedent soil moisture content, storm size and total flow corresponds well with the temporal changes in the relative importance of different trench sections found by *Freer et al.* [2002] for one storm in 1996 during which section A started to produce flow later than the other sections.

6. Conclusions

[28] Our examination of the behavior of the PMRW trenched hillslope based on analysis of 147 rainstorms shows a clear threshold-based response of hillslope subsurface stormflow initiation with storm total precipitation. We detected changes in the relative importance of different parts of the hillslope with changes in total flow, modulated by changes in precipitation and antecedent moisture conditions. We demonstrated the importance of pipe flow for determining the volume of total subsurface stormflow measured at the trench. We found a linear relation between lateral pipe flow and total flow but with seasonal changes in the relative importance of different soil pipes to total pipe flow. These data, showing more flow and more often flow from the high bedrock contributing area sections support the flushing frequency theory proposed by *Burns et al.* [1998]. This analysis also supports the limited role of hillslopes in streamflow production that was inferred from geochemical analyses [*Hooper et al.*, 1998; *Burns et al.*, 2001]. Most importantly, these analyses demonstrate both the importance of record length and the need for analyzing different storm sizes, antecedent conditions and seasons for interpreting hillslope dynamics.

[29] Our work is ultimately an exploration of nonlinear dynamics in subsurface stormflow. Our 147-storm data set shows clearly that outputs are not proportional to inputs across the range of inputs. We argue that this new recognition of a clear threshold behavior may be a way forward in collapsing the vast array of process complexities into a more clear integrated description of hillslope emergent behavior. The "overarching conclusion" of this work though is that the high degree of complexity often observed for single rainstorms on experimental hillslopes, when viewed over a long record, may become much simpler in terms of thresholds that define gross system behavior. This threshold response (both the threshold value itself and the slope of the relation between storm total subsurface stormflow and precipitation after the threshold) may be useful as a tool for intercomparison of the subsurface stormflow response of different hillslopes and could be a benchmark for model calibration and verification. The next paper in this series [*Tromp-van Meerveld and McDonnell*, 2006] explores the process basis for this threshold behavior.

[30] **Acknowledgments.** This work was supported by NSF grant EAR 0196381. We thank Jake Peters for his support for this work, Brent Aulenbach for his help with the data assembly, and Jim Freer and Doug Burns for the initial trench construction efforts. Taro Uchida is thanked for his useful input during a visit to our laboratory. We also thank Markus

Weiler for his help along the way and two anonymous reviewers for their constructive comments.

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