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Hypsometric forcing of stagnant ice margins: Pleistocene valley glaciers, San Juan Mountains, Colorado

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Abstract

Topographic and sedimentological evidence indicates that stagnant ice conditions prevailed during retreat of many Pleistocene valley glaciers in the San Juan Mountains, Colorado. I use topographic data from many of these valleys to test two conceptual models that predict the most likely position for a stagnant ice margin to develop during valley glacier retreat. In the first model, valley hypsometry controls the rate of accumulation area loss for a rise in equilibrium line altitude (ELA). The faster accumulation area is lost, the faster the glacier terminus must retreat, increasing the likelihood of ice stagnation. In the second model, a stagnant margin will develop if a topographic obstacle thins the glacier to a critical thickness, retarding internal deformation and pinching off a section of un-nourished ice.

Comparison of modeling results with field evidence indicates that topographic obstacles do not force the development of stagnant ice margins in the San Juans. Instead, valley hypsometry, in particular the valley slope at the paleo-ELA, appears to be the primary control of ice stagnation. For a constant ELA rise rate, gentle valley slopes force ice stagnation (by increasing retreat rate) whereas steep slopes encourage active retreat. Ice stagnation is prevalent in the San Juan Volcanic Field because incompetent volcanic rocks are easily eroded to produce low valley gradients. This finding that the slope at the ELA is an important control on the development of a stagnant margin is supported by the abundance of stagnant ice deposits in continental settings where the slope at the ELA is very low.

1. Introduction

1.1. Ice stagnation

A retreating glacier can have an active or a stagnant margin. Ice flows continuously to the terminus of a glacier with an active margin. In contrast, internal deformation of ice along a stagnant margin has stopped because the glacier has thinned beyond a critical thickness necessary for flow. This stagnant ice downmelts in place (Jahns, 1941; Flint, 1971, p. 207; Koteff and Pessl, 1981; Gustavson and Boothroyd, 1987). In general, stagnant margins are considered typical of retreating continental glaciers while active margins are thought to be characteristic of retreating valley glaciers.

Many workers have observed stagnant ice at the margin of presently retreating continental and valley glaciers (Table 1). Pleistocene stagnant ice deposits are abundant in areas once covered by continental ice sheets, but they have not been recognized in valley glacier systems (Table 1). This absence of recognized ancient valley glacier ice stagnation can be explained in several ways: (1) ice stagnation did not occur during retreat of Pleistocene valley glaciers; (2) Pleistocene valley glaciers developed stagnant margins during retreat, but deposits have been removed by erosion; or (3) ice stagnation occurred and resulting deposits exist, but previous workers did not recognize the evidence.

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Table 1
Examples of ice stagnation in different glacial settings. Previous workers have not observed ancient stagnant ice deposits in valley or piedmont glacier settings

Type of glacier	Ancient/modern	Location	Author(s)
Continental	Ancient	Appalachian Plateau in western New York	Fleisher, 1986; Cadwell and Muller, 1988
		western sublobe Vashon ice, Puget Lowland, Washington	Lea, 1983
		Adirondack Mts., New York	Gordon, 1941
		Allegheny Plateau, eastern Ohio	White, 1932
		western Vermont	Burt, 1932
		Nashua Valley, New England	Crosby, 1899
		Martian north polar ice cap	Leach, 1983
	Modern	outlet glaciers, east Greenland icecap	Hartshorn, 1961
Small ice cap	Ancient	western Chukotka highlands	Zamoruyev, 1983
		Yellowstone Lake ice cap	Richmond, 1969
Piedmont	Modern	Casement glacier, southern Alaska	Petrie and Price, 1966; Price, 1966; Tuthill, 1966
		Malaspina glacier, southern Alaska	Russell, 1893; Hartshorn, 1952; Gustavson and Boothroyd, 1987
		Martin River glacier, south-central Alaska	Tuthill, 1966; Clayton, 1964
Valley	Modern	Exploradores glacier, Patagonia, Chile	Aniya et al., 1988
		Steele and Klutlan glaciers, St. Elias Mts., Yukon, Canada	Wright, 1980; Sharp, 1988
		Sioux glacier, south-central Alaska	Tuthill, 1966

Here, I report Pleistocene stagnant ice deposits from valley glaciers in the San Juan Mountains, Colorado.

Previous workers have suggested several causes of ice stagnation, including rough topography, surging, thick superglacial debris and rapid climate change (Table 2). Only Fleisher (1986) based observations on more than a single locality. He proposed that stagnant ice formed as the margin of the Laurentide ice sheet retreated through deeply incised, tightly meandering drainages and past "non-through valleys" of the Appalachian Plateau in central New York State. Other workers have also suggested that topographic obstacles force ice stagnation. Price (1966), Shaw (1972), and Cadwell (1981) observed stagnant ice deposits down glacier from bedrock obstacles transverse to ice flow. Others have been less specific, and have suggested that rugged or suitable topography can force a retreating glacier to develop a stagnant margin (Crosby, 1899; Currier, 1941; Sharp, 1953; Koteff, 1974; and Mulholland, 1982).

Wright (1980) and Sharp (1988) observed the development of stagnant ice at the margins of valley and piedmont glaciers that had previously surged. They reasoned that after a surging episode, the glacier terminus is beyond the equilibrium limit controlled by climate. This strands a block of stagnant ice. Tuthill

Table 2
Suggested causes of stagnation for different types of glaciers

Suggested cause of stagnation	Type of glacier	Author(s)
Topography	Continental/piedmont	Crosby, 1899; Currier, 1941; Sharp, 1953; Price, 1966; Shaw, 1972; Koteff, 1974; Cadwell, 1981; Mulholland, 1982; Fleisher, 1986
Surging	Piedmont and valley	Wright, 1980; Sharp, 1988
Thick superglacial debris	Piedmont and valley	Tuthill, 1966, 1968
Rapid climate change	Piedmont and valley	Clark, 1976; Sharp, 1988

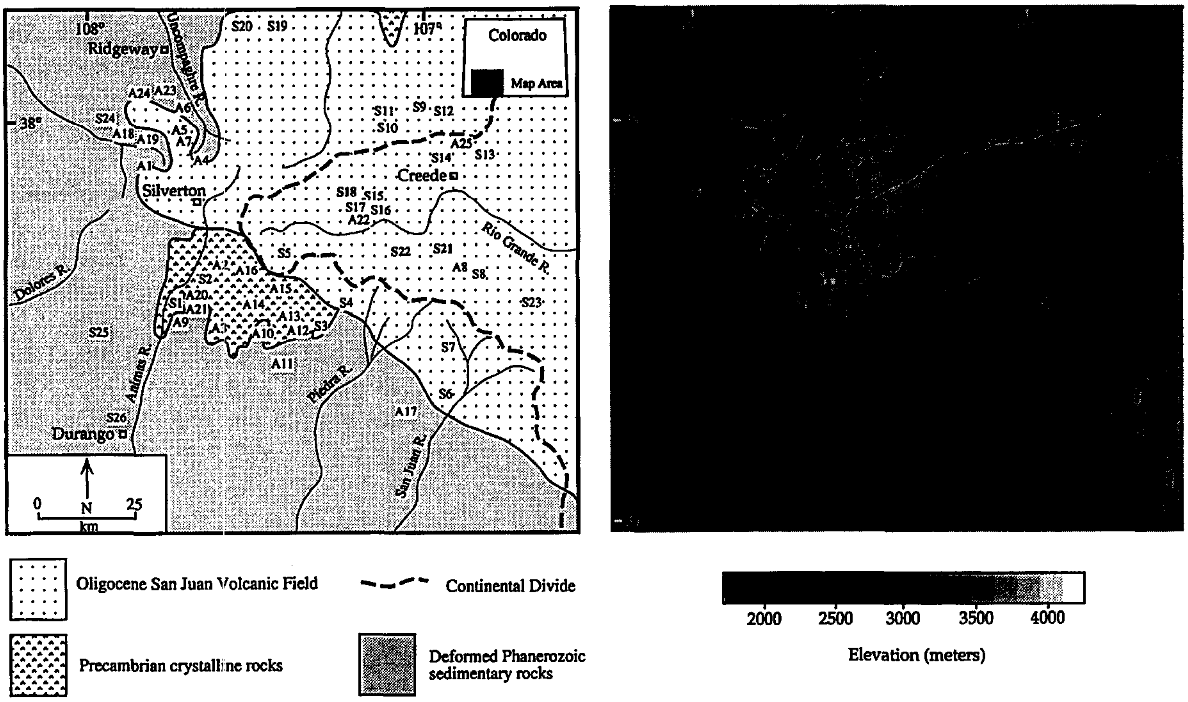

Fig. 1. Left: San Juan Mountains, southwestern Colorado (bedrock after Steven, 1968). Valleys with (S##) and without (A##) stagnant ice deposits are shown. Detailed fieldwork was completed near the town of Creede, in the following valleys (bold type on map): S18 = South Clear Creek; S21 = Middle Branch Roaring Fork; and S22 = Red Mountain Creek. Right: Topography of the same area from 30″DEM data. The continental divide (dashed line) and bedrock contacts are included. Modified from Leonard (1984, p. 66).

(1966, 1968) suggested that thick superglacial debris induced ice stagnation in piedmont and valley glaciers because the weight of debris forced the terminus to extend while debris cover reduced ablation. Clark (1976) and Sharp (1988, p. 122) suggested that a rapid rise in ELA, driven by fast warming and/or drying, can cause stagnation by stranding unnourished ice downstream of a rapidly retreating terminus. In this study, I use the location of stagnant ice deposits in many San Juan valleys to test how valley hypsometry and topographic obstructions influence the type of margin present during valley glacier retreat.

1.2. Study area

I examined deposits of Pleistocene valley glaciers in the San Juan Mountains, Colorado (Fig. 1). I mapped glacial deposits on the eastern side of the San Juans and examined air photos from the entire range.

Few previous workers (Hole, 1912; Atwood and Mather, 1912, 1932; Leonard, 1984) have studied the Pleistocene glacial history of the San Juan Mountains. Atwood and Mather (1912, 1932) completed the most comprehensive study of Pleistocene San Juan glaciers. They reported that three of the six Pleistocene glacial advances of the Western Cordillera could be recognized in the San Juans and produced a 1:125,000 scale map depicting ice limits during these glaciations. Ice covered 5000 km^2 of the San Juans, one-fourth of the entire range, during the peak of the most recent glaciation. Two 1000 km^2 icefields formed over the high mountains and buried the continental divide. Some valley glaciers were fed by these icecaps. In this study, I only examined deposits from the most recent Pleistocene glaciation and from glaciers that Atwood and Mather (1932) mapped as having discrete accumulation areas.

Porter et al. (1983) synthesized previous work and reported that the ELA in the Rocky Mountains was depressed about 1000 m during the last glacial maximum. If deglaciation in the San Juan Mountains occurred over 9000 years (P. Carrara, pers. commun., 1993), then the average ELA rise rate for the region is about 110 m/1000 yr. In the model calculations described below, I assume that this ELA rise rate is constant throughout deglaciation, even though pulses of more rapid ELA rise may have occurred.

Steven (1968) mapped three major bedrock types in the San Juans (Fig. 1). The Precambrian igneous and metamorphic basement rocks are very resistant and are exposed in the cores of anticlines and throughout the Needles Range. This basement rock is overlain unconformably by less resistant sedimentary rocks of Paleozoic through early Tertiary age. Both the crystalline and sedimentary rock types were deformed by the Laramide Orogeny during the late Cretaceous and early Tertiary. The San Juan volcanic field, located in the eastern San Juans, consists of volcanic and laccolithic rocks of Oligocene age. Volcanic deposits include andesite through rhyodacite lavas and breccias, rhyolitic to quartz latitic ash flow tuffs and various fluvially reworked volcanics.

Erosion of resistant Precambrian crystalline rocks and the overlying Paleozoic/Mesozoic sedimentary units produces dramatic peaks and spires in the southwestern portion of the San Juans (Steven, 1968). In contrast, erosion of San Juan volcanic field rocks produces relatively subdued, mesa topography. The contact between the San Juan volcanics and the more resistant crystalline and sedimentary rocks is subparallel to the continental divide, and separates the two contrasting physiographies of the San Juans.

2. Methods

I mapped stagnant and active ice deposits in three valleys (Fig. 1), by constructing plane table and alidade maps and by profiling land forms with an inclinometer and tape measure. Sedimentary sections were recorded and photographed. I noted grain size, sorting, rounding and vertical and lateral changes in sediments.

I examined air photos from the entire San Juan range and found 25 valleys that contained landforms with topography similar to stagnant ice deposits mapped in the field. Atwood and Mather's (1932) surficial geology map was used to verify that these land forms were not landslide deposits, rock drumlins or other features mimicking stagnant ice topography. In addition, I identified 25 valleys that did not exhibit stagnant ice topography. I did not randomly sample valleys from throughout the range to determine the ratio of valleys with and without stagnant ice deposits.

I constructed two conceptual models, described below, to predict the most likely position for a stagnant margin to develop during valley glacier retreat. Data from air photos and maps of 18 valleys were used to simulate Pleistocene glacier retreat. These valleys were chosen randomly from the 50 examined in air photos. Stagnant ice deposits were present in ten of these valleys. A computer simulation used valley floor elevation and valley width measured at 100 m intervals on 1:24,000 topographic maps to model retreat. Valley hypsometry was also calculated from this data. I compared model predictions of the location of stagnant ice deposits to the actual position of deposits found in the field and on air photos to assess the accuracy of the models.

3. Stagnant ice deposits

3.1. Topography

Hole (1912) and Atwood and Mather (1932) described landforms in many areas of the San Juans that are similar to stagnant ice features deposited by continental glaciers (Flint, 1971, p. 207). For example, Hole (1912, pp. 626–627) described the topography in Turkey Creek: ''numerous irregular hills inclose kettles 10 to 15 feet deep and up to 100 feet in diameter. In most directions this hummocky topography continues to the margin of the glaciated area...''. Atwood and Mather (1932) reported that recessional moraines, indicators of active margin retreat, are uncommon in many San Juan valleys.

I field mapped areas with topography similar to Hole's description (Figs. 2 and 3). The following stagnant ice land forms are common: chaotic hummocks (kames), closed boggy depressions (kettles) and sinuous, valley-parallel ridges (eskers) (Flint, 1971, p. 207). Stagnant ice deposits are often immediately upvalley from linear, sharp recessional and terminal moraines, indicators of deposition by active ice processes (Flint, 1971, p. 199). This spatial relationship suggests a shift from an active ice advance or standstill to a stagnant mode of retreat. The average (7.3°) and maximum (16.5°) surface slope angle of stagnant ice landforms is less than that of nearby active ice land forms (13.1° and 24.8°, respectively). These differences in slope suggest that the depositional processes

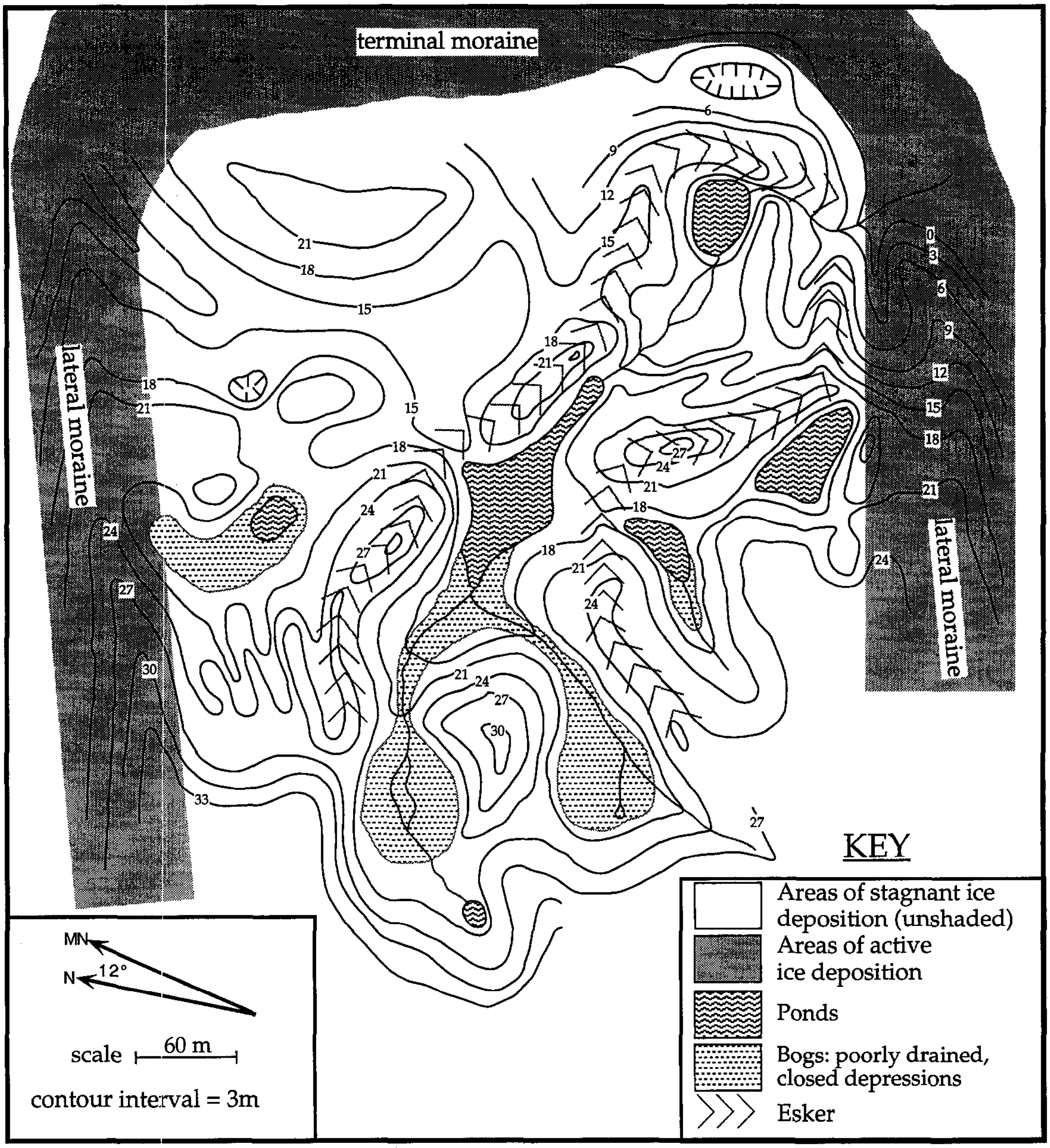

Fig. 2. Plane table and alidade map of stagnant ice deposits in Middle Branch Roaring Fork valley (Fig. 1, S21). Stagnant ice deposits are surrounded by lateral and terminal moraines constructed by active ice processes. Contours are labeled with elevation in meters above the lowest point in the map area. The down-valley direction is towards the top of the page.

that built these stagnant and active ice land forms are not the same.

3.2. Sedimentology

I observed the following sedimentary features in the field that suggest a stagnant ice depositional environment prevailed during construction of the landforms described above: (1) extreme lateral and vertical variability in grain size, sorting and sedimentary structures indicating spatial and temporal heterogeneity in depositional processes (Flint, 1971, p. 184); (2) faulted and tilted bedding from melting of supporting or buried

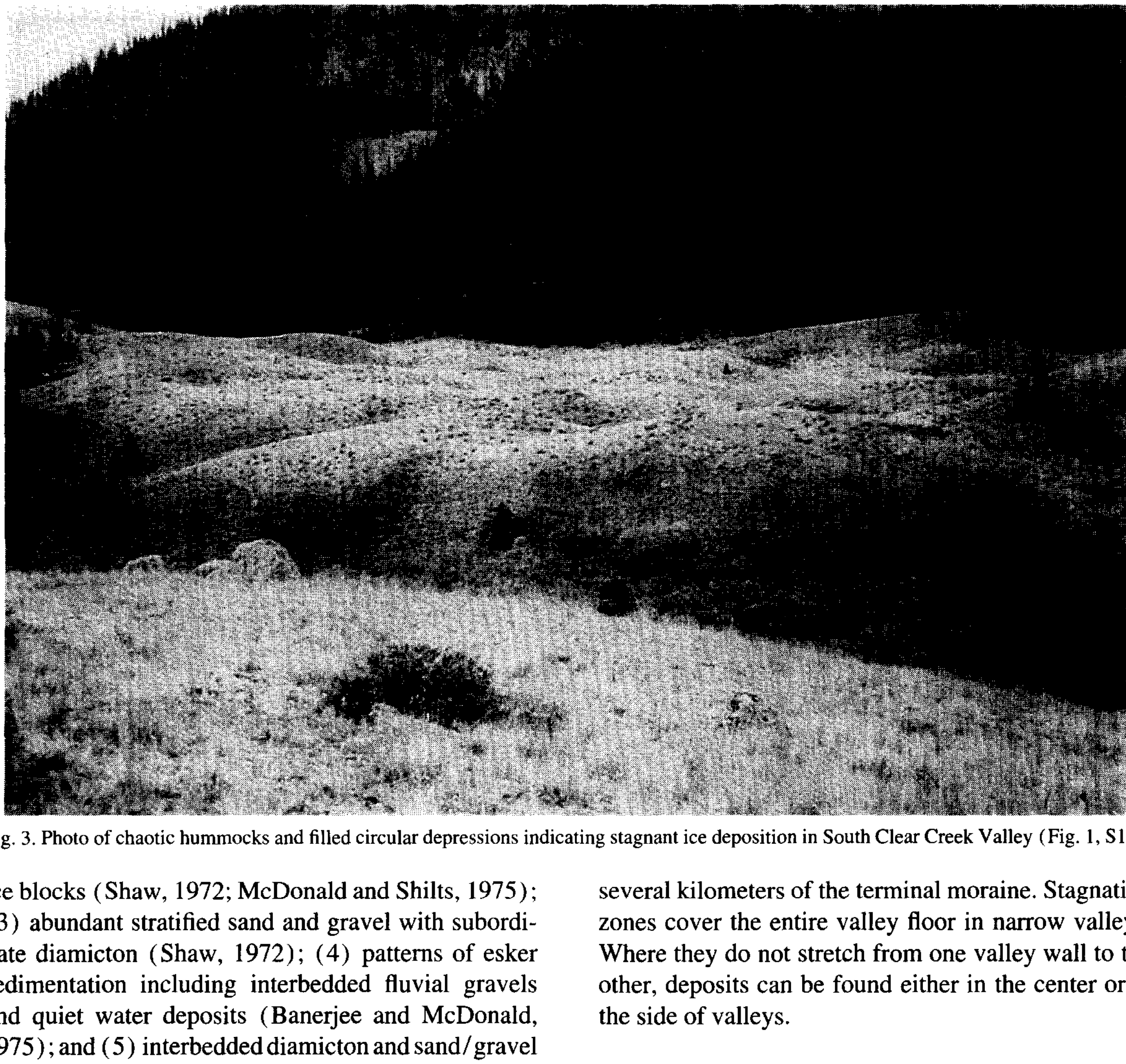

Fig. 3. Photo of chaotic hummocks and filled circular depressions indicating stagnant ice deposition in South Clear Creek Valley (Fig. 1, S18).

ice blocks (Shaw, 1972; McDonald and Shilts, 1975); (3) abundant stratified sand and gravel with subordinate diamicton (Shaw, 1972); (4) patterns of esker sedimentation including interbedded fluvial gravels and quiet water deposits (Banerjee and McDonald, 1975); and (5) interbedded diamicton and sand/gravel or well sorted fines (Paul and Eyles, 1990). In contrast, active ice deposits are more homogenous and are composed primarily of diamicton with only minor components of stratified sand and gravel (Flint, 1971, p. 199).

3.3. Size and location of stagnant ice deposits

Stagnant ice deposits are similar in plan dimension from valley to valley: 200–500 m in the valley-normal direction, and 400–1000 m in the valley-parallel direction. More than 80% of the valleys have a single stagnant ice deposit. The remainder of the valleys have two discrete deposits that are more than 5 km apart. Stagnant ice deposits are most frequently located within several kilometers of the terminal moraine. Stagnation zones cover the entire valley floor in narrow valleys. Where they do not stretch from one valley wall to the other, deposits can be found either in the center or at the side of valleys.

4. Models of stagnant ice retreat

I present here two conceptual models of valley glacier retreat in which the formation of a stagnant margin occurs: (1) when retreat of an equilibrium ice margin is the fastest due to valley hypsometry; and (2) when a topographic obstacle thins the glacier to a critical thickness and pinches off a block of stagnant ice. In both cases, a stagnant margin forms because melt-back of the glacier margin lags behind melt-down upvalley from the terminus.

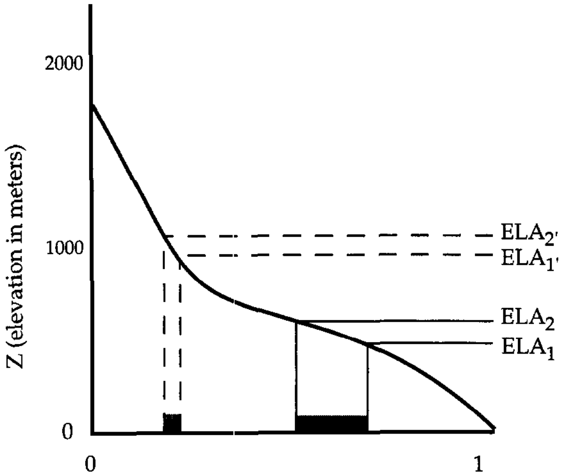

Fig. 4. Generalized cumulative hypsometry of an alpine valley. Because ice surface slope parallels the basal slope up glacier from the terminus, this is also the hypsometry of the valley glacier surface. As the ELA rises from ELA_1 to ELA_2, a relatively large amount of accumulation area is lost (shaded area between solid lines). A much smaller amount of accumulation area is lost for the same magnitude ELA rise from $ELA_{1'}$ to $ELA_{2'}$ (shaded area between dashed lines). The equilibrium glacier margin retreats as the ELA rises, so the elevation of the terminus will be greater than 0 and the area of the glacier will be less than 1 subsequent to a rise from ELA_1.

4.1. Valley hypsometry model

This model is based on the following observations of glacier behavior: (1) surface slope and ice thickness drive internal deformation: as the surface slope or ice thickness decreases, the amount of internal deformation will decrease exponentially (Glen, 1952; Nye, 1952); (2) in a negative net mass balance regime, most mass loss comes from thinning upvalley of the glacier terminus, not retreat of the terminus (Flint, 1947, p. 28); (3) for a glacier in equilibrium, 65% of the glacier's surface is accumulation area above the equilibrium line altitude (ELA) and 35% is ablation area below (Porter, 1970; Meierding, 1982); and (4) greater than 300–400 m upvalley from the terminus, the ice surface parallels the basal surface.

If the rate of ELA rise is constant during deglaciation, the rate of accumulation area loss will vary with valley hypsometry (Fig. 4). When the ELA passes through areas with shallow ice surface slope, a relatively large increment of accumulation area is lost per unit ELA change. Ignoring the response time of a valley glacier, the equilibrium ice margin retreats fastest when the rate of accumulation area loss is greatest (i.e., when the net mass balance of the glacier is most highly negative). At times of rapid equilibrium margin retreat or highly negative mass balance, the ice thickness near the terminus is low. Basal shear stress and ice flow decline under these conditions, promoting the development of a stagnant margin if melt back of the glacier margin does not keep up with the rapid thinning.

This model relies on the following assumptions: (1) ice at a glacier margin becomes stagnant as internal deformation decreases. Basal sliding is not important when differentiating between an active and a stagnant margin; (2) ELA rise rate is constant throughout deglaciation; (3) the lag time between ELA rise and adjustment by the glacier terminus is constant; (4) a retreating valley glacier preserves the 0.65 accumulation area ratio (AAR) observed for glaciers in equilibrium; (5) deviations from a 0.65 AAR due to glacier hypsometry (Furbish and Andrews, 1984) are negligible. The positive results reported below suggest that these assumptions are valid for the purpose of this model.

I constructed a computer model that uses valley hypsometry to calculate the equilibrium ice margin retreat rate at all points during deglaciation. If the ELA rise rate is constant, then the equilibrium ice margin retreat rate depends only on the ice surface slope at the ELA, and the widths of the glacier at the ELA and the terminus. For a known ELA rise, the amount of lost accumulation area is calculated depending on the surface slope and the width of the valley at the ELA (Fig. 5). The amount of ablation area lost with this ELA rise can be determined following the 65%/35% area split around the ELA. The distance the glacier terminus retreats due to an incremental rise in ELA is the sum of the accumulation area loss divided by the valley width at the ELA and the ablation area loss divided by the valley width at the terminus (Fig. 5).

I used valley floor elevation and width from 18 valleys to calculate the position in a valley where the equilibrium ice margin would be retreating most rapidly according to valley hypsometry. This location represents a prediction of the most likely place for a stagnant margin to develop. I then compared the predicted position to the location of stagnant ice deposits found in the field.

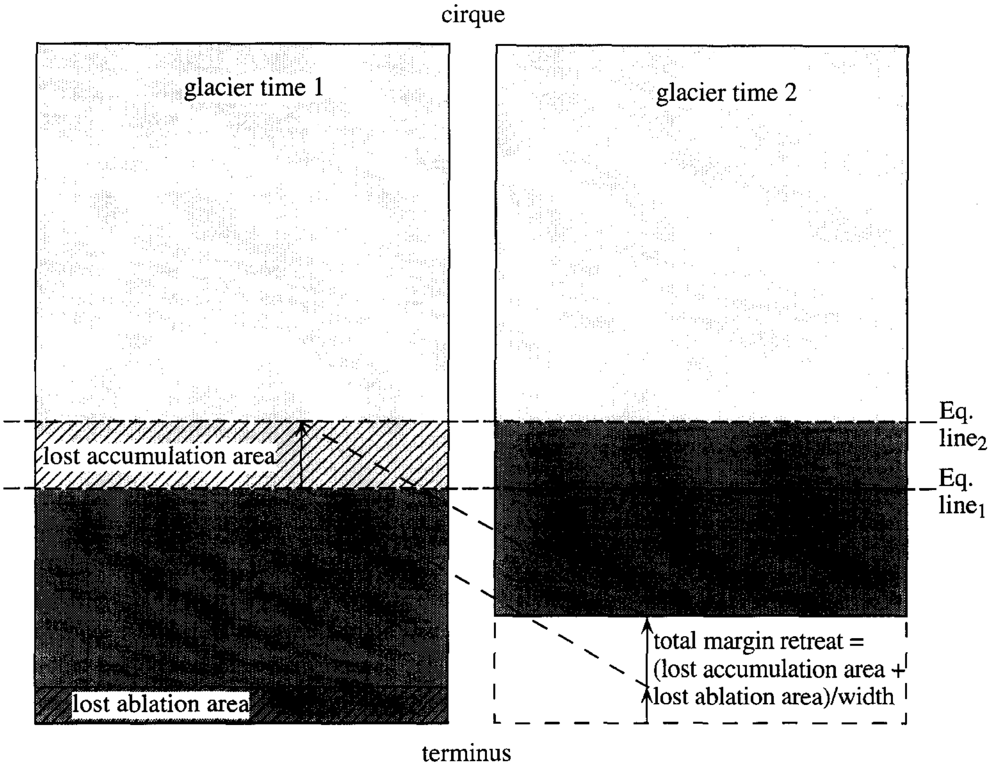

Fig. 5. Map view of a simplified retreating valley glacier at two times. The dashed lines are the equilibrium lines at times 1 and 2 and separate the accumulation area (light gray) from the ablation area (dark gray). The hatched rectangles represent the lost accumulation and ablation areas due to a rise in ELA which shifts the equilibrium line up-glacier. The distance the margin retreats is the combined loss in accumulation and ablation areas divided by the glacier width.

4.2. Critical thickness model

This model was used to determine if topographic features present in San Juan valleys could lower ice thickness enough to reduce internal deformation somewhere up from the terminus, creating a stagnant margin (Fig. 6). Only bedrock features with valley-axial lengths less than several hundred meters will thin a glacier because the ice surface parallels larger scale topography. A glacier is not sensitive to bedrock obstacles several kilometers upvalley from the terminus because ice thickness is much greater than the height of the obstruction. However, as the equilibrium glacier margin retreats, the amount of ice overlying the obstacle diminishes and the influence of the obstacle on ice thickness and internal deformation increases.

I calculated ice surface profiles for San Juan valley glaciers every 100 m during retreat, following the "valley" method described by Schilling and Hollin (1981). Profiles were calculated with an average basal shear stress of 1 bar over a 500 m step length. This calculated ice surface and measured bedrock profiles were used to calculate ice thickness at 100 m steps along the glacier. These ice thickness values were then used in Nye's equation for shear stress (Nye, 1952, 1965) to determine a local shear stress between the 500 m step end points. I recorded the ice margin positions in a valley where topography most greatly reduced the local basal shear stress; again, these would have been the most likely places for ice stagnation to occur. This model ignores the possibility that longitudinal stresses within the glacier can push or pull thin ice past a topographic obstruction.

5. Results

Stagnant ice deposits are found where the equilibrium glacier margin would be retreating most rapidly according to the valley hypsometry model (Fig. 7).

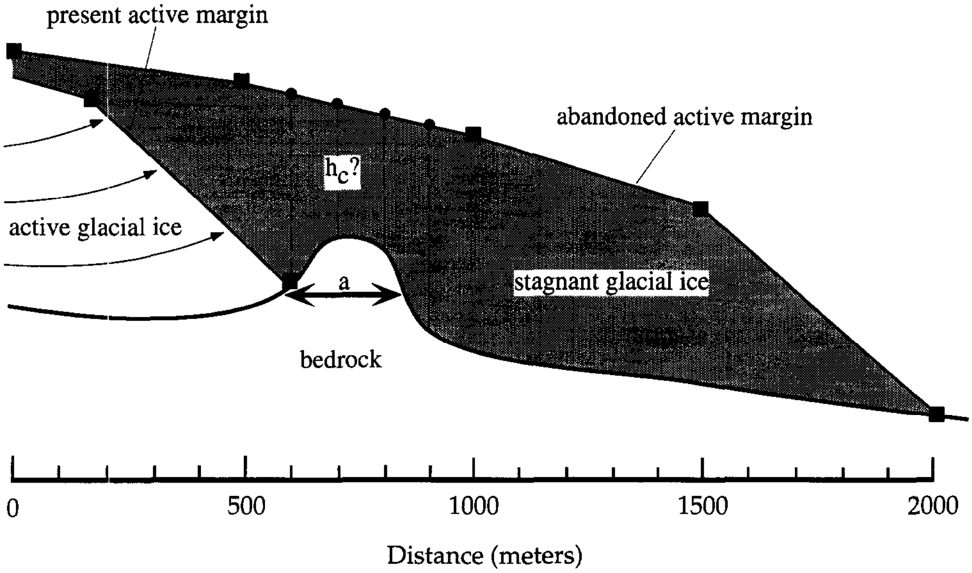

Fig. 6. Longitudinal profile of the terminus of a retreating valley glacier. A block of stagnant ice (gray) is isolated from the active glacier when a bedrock obstacle thins the ice to a critical thickness (h_c). The active margin retreats to a position where glacier thickness is great enough for flow. Only a bedrock obstacle that has a valley-axial length, a, less than several 100 m will thin the ice (portrayed here). If a is greater than several 100 m, the ice surface will parallel the basal surface and the ice will not be thinned. The ice surface is calculated over a 500 m step length (squares on ice surface profile). Ice thickness is measured at 100 m intervals between step end points (dots and dashed lines shown only over bedrock bump).

Each point represents the observed and predicted position of a distinct stagnant ice deposit. Half of the observations are from valleys with single stagnant ice deposits. The other half are from valleys with two separate deposits. In these valleys with two deposits, two retreat rate maxima were predicted. Each predicted maximum was then compared to the closer observed deposit. The 1:1 reference line represents perfect prediction. All but one point tightly cluster around the reference line.

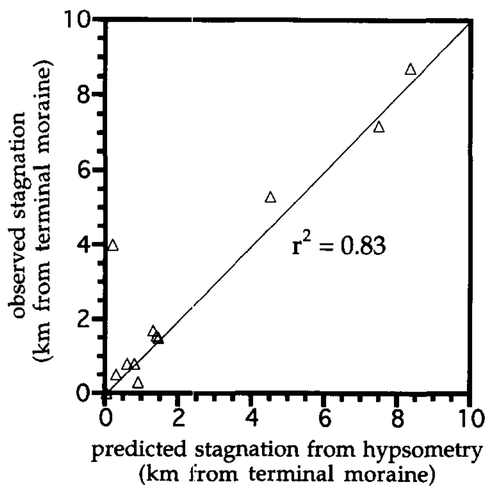

Fig. 7. The location of ice stagnation predicted by the valley hypsometry model compared to the location observed in the field for 12 stagnant ice deposits in 9 valleys.

The maximum equilibrium retreat rate (mean of the 5% most rapid retreat rate values for a valley) calculated using the hypsometry model is greater in valleys with stagnant ice deposits than in valleys without stagnant ice deposits (Fig. 8). This difference is significant ($p < 0.01$: Mann–Whitney U-test). Cumulative hypsometric curves show the rate of accumulation area loss with increasing ELA is greater at most points, not just at maxima, in valleys with stagnant ice deposits than in valleys without stagnant ice deposits (Fig. 9).

Valleys with stagnant ice deposits are located in the San Juan Volcanic Field, while valleys without stagnant ice deposits are located outside of this area (Fig. 1 and Table 3). This difference is significant ($p < 0.001$: Chi square test).

The critical thickness model does not accurately predict the location of stagnant ice deposits (Fig. 10). This is consistent with my observations on maps and air photos that stagnant ice deposits are not adjacent to topographic obstacles that might induce stagnation.

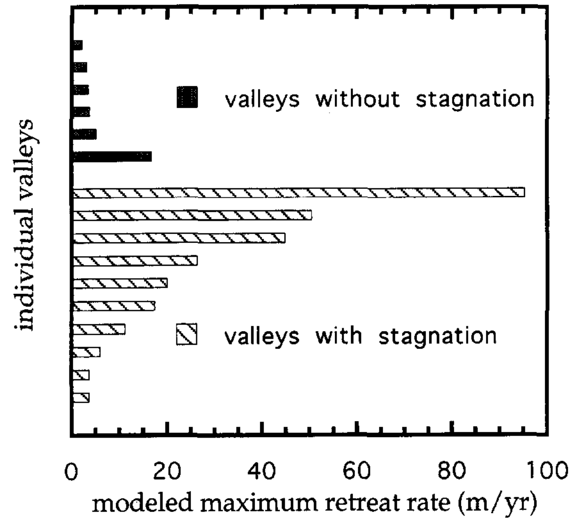

Fig. 8. Maximum retreat rate calculated with the hypsometry model for valleys with and without stagnant ice deposits, calculated with an ELA rise rate of 110 m/1000 yr.

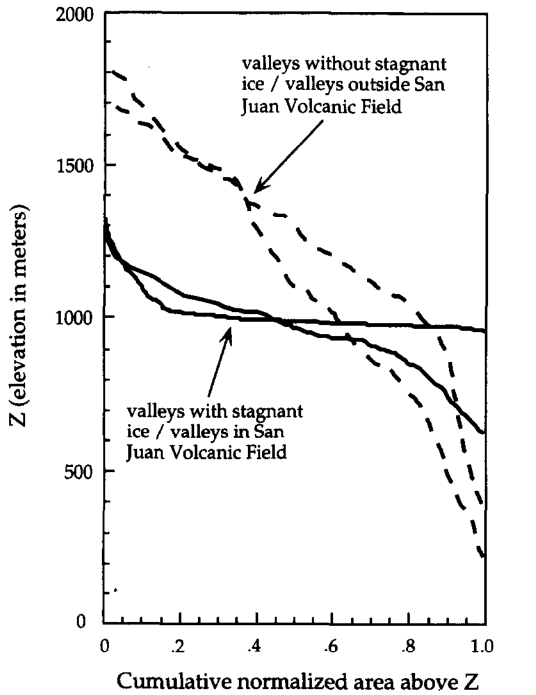

Fig. 9. Cumulative hypsometries of two typical valleys with stagnant ice deposits in the San Juan Volcanic Field (solid lines) and two typical valleys without stagnant ice deposits outside of the San Juan Volcanic Field (dashed lines). The curves have been translated vertically to facilitate comparison, so elevation, Z, is not absolute.

Each point in Fig. 10 represents the observed and predicted position of a distinct deposit in eight valleys.

Table 3
The number of valleys found with and without stagnant ice deposits inside and outside of the San Juan Volcanic Field

	San Juan volcanic Field	Other bedrock types
Valleys with stagnant ice	20	5
Valleys without stagnant ice	6	18

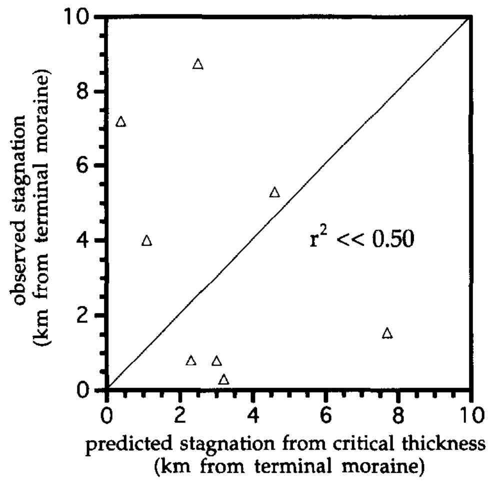

Fig. 10. The location of ice stagnation predicted by the critical thickness model compared to the location observed in the field for 8 stagnant ice deposits.

Two of these observations are from valleys with two separate deposits. In these two valleys, I compared the predicted position with the closer observed deposit. All eight deposits in Fig. 10 were also examined in Fig. 7.

6. Discussion

Valley hypsometry appears to have controlled the development of stagnant ice margins during retreat of Pleistocene valley glaciers in the San Juan Mountains. Stagnant ice deposits are found where the glacier margin would retreat most rapidly when controlled by valley hypsometry alone (Fig. 7). Rate of retreat at these points is faster than the maximum retreat rates in valleys without stagnant ice deposits (Fig. 8).

Valley slope and width at all points along a valley determine the hypsometry and resulting retreat rate. Valley width varies little along San Juan valleys, implying its effect on hypsometry is minimal. Variations in slope within and between valleys are great and control changes in hypsometry. Slope by itself can therefore be used as a proxy for rate of accumulation area loss with ELA rise. Shallow slopes at the ELA force the development of a stagnant ice margin while steep slopes encourage active retreat.

Bedrock controls valley hypsometry in the San Juan Mountains. San Juan Volcanic Field rocks are easily eroded to shallow slopes, producing a hypsometry where rate of accumulation area loss with ELA rise is high (Fig. 9). Tougher crystalline and sedimentary rocks are not easily eroded. Slopes are steep in these valleys and hypsometry produces low rates of accumulation area loss and of equilibrium margin retreat. This hypsometric difference between bedrock types could explain the abundance of valleys with stagnant ice deposits within the San Juan Volcanic Field.

The abundance of valleys with stagnant ice deposits within the San Juan Volcanic Field could also indicate that thick superglacial debris from cliff failure of weak bedrock forces ice stagnation, as suggested by Tuthill (1966, 1968). Two observations suggest that thickness of cliff derived superglacial debris is not as important a control as valley hypsometry: (1) Thick, sandy diamicton caps indicating the presence of superglacial debris are only found on top of some, not all, stagnant ice deposits, and (2) Near-vertical cliffs along the entire length of most San Juan Volcanic Field valleys were below the ice surface during the glacial maximum (Atwood and Mather, 1932). As ice retreated, these cliffs were exposed and their potential for supplying superglacial debris increased. The location of most stagnant ice deposits indicates dead ice was present at ice margins at or near the glacial maximum when debris production from cliffs would be at a minimum.

Topographic obstacles do not seem to control ice stagnation during retreat of San Juan valley glaciers. San Juan valleys were strongly modified by glaciers. Bedrock knobs and ridges that would force a glacier to thin to a critical thickness are uncommon, perhaps because these features have been removed by glacial erosion. Continental glacier margins, on the other hand, retreat past topography often created by processes other than glacial erosion. Topographic obstacles to glacier flow are more common in these situations and could play a more important role in inducing ice stagnation.

The hypsometry and surface slope of continental ice sheets is conducive to the formation of a stagnant ice margin because the rate of accumulation area loss with ELA rise is very high. For the same change in ELA, the continental glacier retreat rate will be much faster than that of a valley glacier. This could explain the greater abundance of stagnant ice deposits in continental glacier settings.

Results from the hypsometry model suggest that ice stagnation can occur with a constant ELA rise rate. Rapid climate change will also increase the likelihood of developing a stagnant margin by increasing the rates of accumulation area loss and margin retreat. However, the presence of stagnant ice deposits in itself does not necessarily indicate a period of more rapid climate change, as suggested by Sharp (1988) and Clark (1976).

7. Conclusions

(1) Stagnant ice margins were common during retreat of Pleistocene valley glaciers in the volcanic San Juan Mountains, Colorado.

(2) Valley hypsometry is an important control of ice stagnation in retreating valley glaciers. A stagnant margin is most likely to develop at the terminus when the rate of accumulation area loss from an increment of ELA rise is the greatest. Valleys with hypsometries that cause rapid rates of accumulation area loss have stagnant ice deposits while valleys with hypsometries that induce slower rates of accumulation area loss do not. Valley axial slope can be used as a proxy for rate of accumulation area loss with ELA rise. Shallow slopes force the development of a stagnant margin while steep slopes encourage active margin retreat.

(3) Volcanic rocks of the San Juan Volcanic Field erode to shallow valley slopes, encouraging ice stagnation. Stagnant ice deposits are uncommon in steep valleys cut through tougher bedrock in other areas of the San Juans.

(4) Topographic obstacles that could induce ice stagnation are rare in San Juan valleys and stagnant ice deposits are not located near the few obstacles that do exist.

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