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## Alluvial Fan Development at Franklin Bluffs, Alaska

GARY S. ANDERSON<sup>1</sup> AND KEITH M. HUSSEY<sup>1</sup>

*Abstract.* This paper is concerned with the developmental history of alluvial fans forming in a tundra climate. The study was made at Franklin Bluffs, Alaska ( $69^{\circ} 48' - 70^{\circ} 00' N$ ,  $148^{\circ} 40' W$ ), during the summer of 1961. The area is an ideal place in which to study the developmental history of alluvial fans in that so many stages are present in a relatively small area.

A theoretical sequence of fan development was set up, illustrated by examples from the Franklin Bluffs, which show how certain characteristics of an alluvial fan, forming in a tundra climate, change as the sequence advances. The sequence was designated A, B, C, D, and E, where A is the youngest, near talus cone stage, and E is the oldest, near graded stage.

Certain characteristics were found to constitute a continuum of changes in the sequence. The two most continuously changing factors are the difference in slope, between that of the drainage area and that of the fan, and the relative size of each fan -vs- drainage area. Also, in the progress of the sequence, the intensity of mass wasting decreases. Related to the type and intensity of mass-wasting are the amount and size distribution of surficial rock material and the amount and type of vegetation. The climax of the sequence is characterized by the approach to a well vegetated graded stage on which a permanent channel forms if sufficiently continuous discharge is present.

An alluvial fan is an expression of a stream's inherent power to adjust its profile to a graded stage for the conditions present. The establishment of a graded fan goes through sequential stages of development. The Franklin Bluffs area is an ideal place in which to study this sequential development in that so many stages are present in a relatively small area.

The Franklin Bluffs are situated between latitudes  $69^{\circ} 48'$  and  $70^{\circ} 00' N$ , and at longitude  $148^{\circ} 40' W$ , on the Arctic Coastal Plain Province of Northern Alaska (Fig. 1). The bluffs themselves consist of two areas of relatively high relief which are conveniently termed the Northern and the Southern Sections. The northern portion of the Southern Section is the area specifically concerned with in this paper. At the northern end of this section, the bluffs have an average of about 100 feet of relief, and reach a maximum height of 500 feet above the river at Bruce Benchmark, which is at the southern end of the section.

The bluffs are formed in the northeast dipping Sagavanirktok

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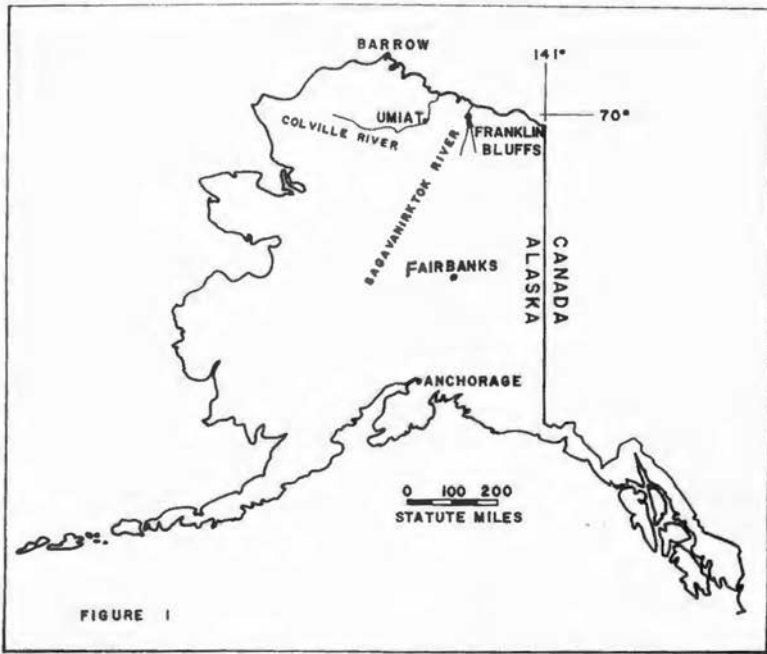


FIGURE 2

Figure 1. Map of Alaska showing location of Franklin Bluffs.  
Figure 2. Oblique view looking south along the Southern Section of Franklin Bluffs. Fans D and E are seen adjacent to the large channel-scarred terrace in the lower-middle part of the picture. Fan B is found further to the south and is now in contact with a tributary of the Sagavanirktok River.

formation whose members variously consist of poorly consolidated conglomerates, sandstones, and siltstones with interbeds

of shale and coal (Keller, Morris, and Detterman, 1961, p. 207). That section of the formation exposed in the area of study is comprised predominantly of gravels ranging from small pebbles to small boulders, with various amounts of silt and sand. With the exception of one three-foot iron-cemented bed, the gravels are cemented only with ice. Thus, during the summer, the gravels are totally uncemented at the surface, but well cemented below the depth of thaw.

The amount of runoff water along the Bluffs greatly exceeds that which the tundra climate could produce. The excessive runoff is the product of thaw of the great accumulation of wind-drifted snow which collects in considerable thickness in the sheltered ravines, which feature the deeply dissected face of the Bluffs. These pockets of snow commonly have an early spring depth in excess of 20 feet and persist through much of the summer, in spite of almost continuous melting. They supply the water essential to growth of the fan. Some runoff water is also supplied from the thaw of frost and the occasional rains.

The shear, west-facing scarps of the Franklin Bluffs owe their existence to the eroding ability of the Sagavanirktok River. Here, where the formation has been upwarped, the river has carved away the western half of the structure, leaving a broad, flat, miles-wide valley bottom to the west as it slips-off, down-dip, maintaining a steep eastern margin where it has impinged against the Bluffs. Today, in the vicinity of the bluffs, the river pursues a subsequent course along the strike of the northeast-dipping Sagavanirktok formation. Active channels of the river are not everywhere impinging against the bluffs. Often there is some considerable expanse of flood plain, former terraces, bars, and/or fans between any present-day active channel of the river and the bluffs. However, these are only temporary obstructions, and that portion of any of them which is in contact with a channel of the river is usually being actively eroded. The proximity of the river to the bluffs, and the length of time a particular relationship has existed, determines the developmental stage and activity of the fan-building processes. Along the length of the bluffs, there are fans in all stages of development which show the results of all degrees of activity.

In the recent past the river has actively eroded the bluffs at the north end of the Southern Section. There, the cutting was so rapid and extensive as to remove not only the pre-existing fans but also their upland drainage areas. We are thus provided with an excellent example of the relationship between first-cycle fans and their drainage areas. In this segment of the bluffs, they have about equal proportions. The north to south increase in

the surface area of the individual fans, and their related drainage areas, reveals the continuing shift of the river away from the bluffs. The largest fan in this vicinity is the oldest. It was formed first, and continued to grow while the other fans were being progressively initiated toward the north. Shortly after the youngest fan began to form, at the more northerly end of the Southern Section, the more eastward channels of the river were abandoned. This is evidenced by the large, channel-scarred terrace between the present easternmost channel and the bluffs (Fig. 2).

Immediately, as a channel of the river is shifted away from direct contact with a segment of the bluffs, the struggle of the upland drainage to maintain connection with the river is initiated. Gullies that form in the face of the bluffs terminate in fans along their base. Thus will be initiated the drainage area-alluvial fan pair which results from the changing ability of the "stream" to erode and transport, and leads to adjustment of the profile. Each part of the pair naturally increases in area with time. Hence, the relative size of such a pair can be used as an indicator of its age. Unless some other factor is introduced, growth of the two areas will continue until the drainage area becomes large enough to catch sufficient snow, to support a permanent stream throughout the thaw season, and the fan will be extended sufficiently to carry the flow of water to the river. In effect, a graded profile will be established.

One example of the introduction of "another factor" can be noted just to the south of that section of the bluffs which is adjacent to the terrace. There, the river is presently close to the bluffs and apparently has been there for several years (Fig. 2). The constant removal of material from the distal ends of the fans slows progress towards an equilibrium profile. The drainage areas in this portion of the bluffs are much larger than the fans, and are continuing to grow. In this area, if the present condition obtains, the graded profile will develop largely in the drainage area.

It seems valid to set up a theoretical sequence of fan development, illustrated by examples from the Franklin Bluffs, which show how certain characteristics of an alluvial fan forming in a Tundra Climate changes as the sequence advances. The sequence will be designated A, B, C, D, and E — where A is the youngest, and E the oldest. Fans A, C, D, and E have been picked from the northern end of the Southern Section which is now separated from the river by an extensive terrace. Fan B is located to the south where the river is actively eroding its distal end and thus keeping it very active, not just because of its prox-

imity to the river, but also, because of greater height of the bluffs and the greater snow accumulation in the drainage area above the fan. Its morphological characteristics place it between Fans A and C (Fig. 2).

There are certain characteristics which constitute a continuum of changes in the sequence. The two most continuously changing factors are the difference of slope, that of the drainage area and that on the alluvial fan, and the comparative size of each of the units. In the progress of the sequence, the intensity of mass wasting decreases. Ideally this is a regular progression, as illustrated by the A, C, D, E series of fans, in which the intensity of material movement is progressively decreasing. However, Fan B does not fit into the sequence, because the continuous erosion of its distal end alters the rate of any trend toward development of a graded slope. It is included in the sequence because of its morphological characteristics, and because of the good examples it shows of material movement on a young fan. Related to the type and intensity of mass wasting are the amount and size distribution of surficial rock material, and the amount and type of vegetation. The climax of the sequence is characterized by the approach to a well-vegetated, graded stage on which a permanent channel forms if sufficiently continuous discharge is present.

In the proposed sequence, the amount of difference between slope of the drainage area and that of the fan is more significant than degree of the slope in each case. The slopes on the individual fans vary greatly with difference in local controlling factors; therefore, the actual degree of slope is not an indicator of morphological age. In the initial stage, both slopes are high and similar; therefore, the slope difference is slight. However, as the fan develops, its slope is reduced and the corresponding angular difference between fan and drainage area increases. Then, as the drainage area is extended and its slope is correspondingly reduced, the slope difference decreases until it is very small as the graded stage is approached. Plates I and II show the progressive change in the amount of slope angle difference for the proposed sequence of fans.

The other uniformly changing factor is the relationship of drainage area size to fan size. In the near initial stage of the sequence, the fan and drainage area are close to the same size. Then, as the drainage area channels become incised, the fan continues to increase its surface area. In the proposed sequence, the near graded stage has a drainage area that is actually larger than the fan. For a comparison of fan and drainage sizes in the series, see the figures on Plates I and II.

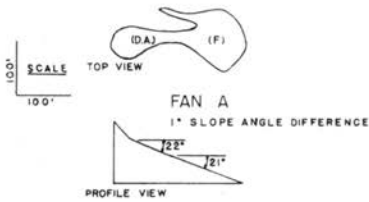


FIGURE 3

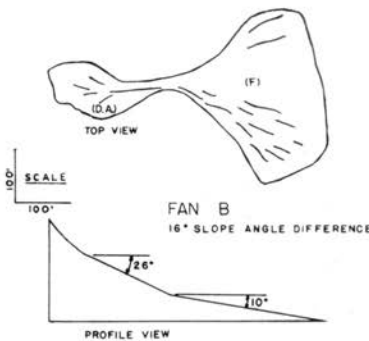


FIGURE 4

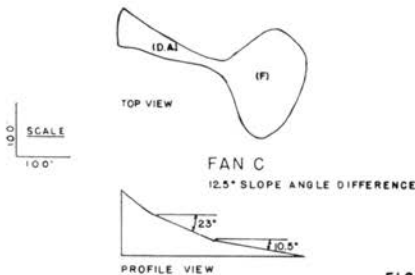


FIGURE 5

Figures 3, 4, and 5. Schematic diagram showing relative size of alluvial fan — drainage area pair and the slope angle difference between the two. Located adjacent to each diagram is the corresponding photograph of the fan.

Although the intensity of mass wasting is generally an indicator of the stage of the fan in the sequence, as has already been pointed out, Fan B is an exception. It is quite large, and yet shows evidence of much movement of material. Movement appears to be most active in the early spring when a relatively large quantity of water is being released by melting snow. This water picks up debris in the drainage area and runs onto the fan where it becomes concentrated in channels of various forms. Normal channels, or washes, are well developed on the north side of the fan and on the south side where they vary in size, and

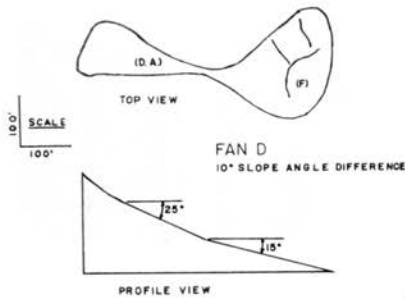


FIGURE 6

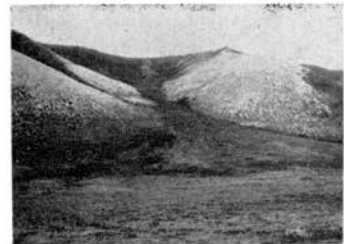
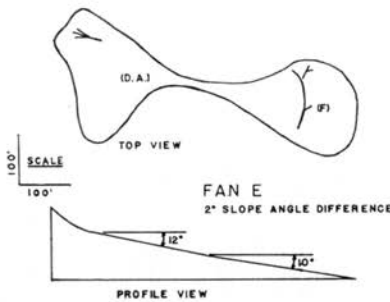
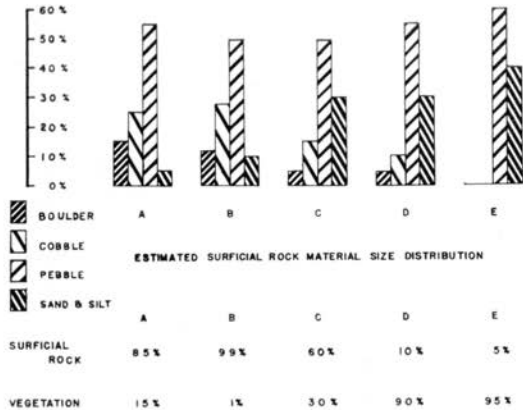


FIGURE 7



ESTIMATED SURFICIAL ROCK MATERIAL SIZE DISTRIBUTION  
ESTIMATED PERCENTAGE SURFACE COVER ROCK V.S. VEGETATION  
FIGURE 8

Figures 6 and 7. Schematic diagram showing relative size of alluvial fan-drainage area pair and the slope angle difference between the two. Located adjacent to each diagram is the corresponding photograph of the fan.

Figure 8. Histogram showing estimated surficial rock material size distribution (top), and estimated percentage surface cover rock versus vegetation (bottom).

all display a concentration of coarse material as a result of removal of the fines. Some of the normal channels were occupied by running water at the time of study, from early July to the middle of August.



The bottom of such channels is not appreciably lower than the level of the fan surface, but the sides have apparently been built up by a combination of processes. As a tongue of mud moves down the fan, material is pushed aside in a snowplow fashion at the distal end of the tongue; and, as temporary dams form along the length of the channel, viscous graveliferous mud overflows the channel, loses its fluidity, ceases to flow, and thus becomes a material deposit on the natural levee.

On the middle and south side of the fan, relatively large lobate deposits were found. These are believed to be the lag deposits of former unconfined mudflows that did not have the proper consistency to form natural levees.

The surficial distribution of material on Fan B indicates that mudflows are an important mode of transportation on a young fan in the sequence. The present surficial material on Fan B is predominantly coarse, but it is assumed that fines were abundant in the viscous mass that originally moved on the fan since fines are required in a mudflow, and the source area does have an admixture of a wide range of sizes of material. Consequently, the mudflow levees and mudflow lobes must have originally contained fines which have since been removed by wind and rain. Robert P. Sharp (1942) describes mudflow activity in the St. Elias Range, Yukon Territory, that occurred under conditions very similar to those found at Franklin Bluffs. He also found concentrations of boulders in the form of natural levees and lobated features which he explains as the lag deposits of former mudflow activity.

A fan located directly north of Fan B has characteristics very similar to it. Late in the season, a mudflow became very active on the fan. The water for the mud flow was coming from beneath the snow bank in the drainage area. The flow increased in amount by a quantity more than could be expected from daily thaw of ground frost and snow melt. During the first part of the season, the snow bank in the drainage ravine was quite large and over 20 feet deep. However, during the six weeks previous to the time of the observed mudflow, the snow was subject to almost continuous thaw. The bank had been so reduced in size that it covered only the bottom of the ravine, and was only about three feet deep. Apparently the melt water had produced a depression of the permafrost table under the snow bank, which created a natural subsurface reservoir. The contained water caused expansion of the reservoir, and permitted additional accumulation of melt water from the snow bank and ground frost. As the snow bank wasted away and, as the active layer in the area around the perimeter of the snow bank deepened, the reservoir, was tapped and supplied the water required for activat-

ing a mudflow. As melt water came out of the bluffs, it caused the gravels to slump into the drainage ravine. The sand, silt, and water combined to form a very dense fluid mass which rapidly flowed down a channel in the bottom of the ravine. Particles ranging in size up to 24" boulders were incorporated and carried along. In places the viscous mud overflowed the channel, lost its competency, and deposited coarse material on the levee. The material that remained in the channel was carried to the fan and deposited on it. Near the apex of the fan, boulder and cobble material was deposited in lobate patterns which had a maximum relief of four inches.

Slope was found to be a very critical factor in determining what size material could be carried. The slope at the head of the ravine, from where the material was coming, ranges between 30° and 90°. At the upper end, just below its head-end, the slope of the ravine dropped abruptly to 19°, and decreased slowly from there to its lower end where the slope is 14°. Along these slopes, material of all sizes was intermittently carried. The larger rocks were often temporarily at rest when the mudflow became very liquid, but as the sand-silt portion of the flow increased, the cobbles and boulders were again moved down the channel. The slope of the fan ranges from 9° at its apex to only 3° at its distal end. There is a distinct size grading of material on the fan. On the upper one-third, it consists of: 10% boulders; 30% cobble; 20% pebble; and 40% sand and silt. The middle one-third; 5% boulder; 15% cobble; 30% pebble; and, 50% sand and silt. The lower one-third, where the slope is 3°: 90% sand and silt a 10% assortment of boulders, cobbles, and pebbles.

Fan B, and its neighbor, display much more evidence of intensive mass wasting than any of the other fans in the sequence. The other fans—A, C, D, and E—show a progressive decrease in intensity of mass wasting and, on these fans, gravity is the most important transporting agent, as compared to the channelized alluvial and mudflow transportation on Fan B.

On Fan A, the most active of the four, material comes onto the fan from the vegetation-barren drainage area by rockfall. Surficial movement of material on the fan is primarily by rock creep, which is evident from the concentration of cobbles and boulders at the distal end. Numerous steps have formed on the fan that indicate mass movement along a number of slippage planes.

Fan C is slightly more stable than Fan A. The drainage area is also barren of vegetation, and material moves from there to the fan by rock fall and upper slope wash. There is a pattern affect on the fan caused by stripes of gravel separated by stripes of

vegetation. The stripe pattern, as compared to steps, shows greater slope stability as well as a certain amount of channelized movement.

The transition from C to D shows a great increase in stability and the corresponding decrease in intensity of mass wasting. The drainage area is cirque-like in nature, and is featured by numerous well-vegetated solifluction lobes. Downslope movement in the drainage area is made evident by large chunks of tundra vegetation mat which have broken loose and moved downslope so as to expose the underlying gravels. The ravine in the bottom of the drainage area is choked by a large solifluction lobe. Because of the fairly well vegetated drainage area and the solifluction lobe choking the drainage ravine, a very limited quantity of rock debris can move from the drainage to the fan. At the present time, rock debris is being delivered to the fan from the steep bluffs adjacent the apex of the fan. These bluffs have a slope of approximately  $30^\circ$  with numerous scree stripes near their base. The bare-gravel scree stripes are separated by stripes of vegetated surface. The vegetation stripes appear to be stable, but the bare rock is obviously moving downslope. Movement is not perceptible, but the lower ends of the rock stripes have a concentration of boulders that are oriented in a manner indicating movement. Occasionally some of the boulders from the distal ends of the stripes roll onto the fan. Further movement of the boulders that roll onto the fan is by rock creep.

In addition to the small quantity of rock creep on the fan, there is one other type of mass wasting. This is a large slumpage of the lower one-third of the fan. The fact that slumping has occurred is made evident by an extensive fracture network that has formed on the surface of the fan (Fig. 6, Plate II). Gravity, aided by the increased concentration of water in the lower end of the fan, is responsible for this slumpage.

Fan E shows the greatest degree of stabilization in the proposed sequence. There is almost a total absence of mass movement. In the head-end of the drainage area, vegetated solifluction lobes are evident, but the vegetation mat is seldom broken. The only movement on the fan proper is an extensive slumpage at its lower one-third. The mechanics of this slump seems similar to that on Fan D, and the resulting fracture pattern is very similar.

In addition to age indicators of the fans that have already been pointed out, the characteristics of the upland tundra above the drainage area and the method by which the vegetation mat moves into the drainage area are also good indicators of the relative age of fans. Fan A is so young that its drainage area

has not extended into the upland tundra. The drainage area of Fan B has invaded the upland tundra only to a small extent. However, there is a small series of steps that have formed on the adjacent upland from slumpage toward the drainage area, and some of the tundra mat has caved off the bluffs into the drainage area. Hawk Creek has eroded into the gravels on the east side of the bluffs, and thus reduced the divide between it and the Sagavanirktok flood plain to a serrated gravel ridge. Above the cirque-like heads of the drainage areas above Fans D and E, thaw of ground-ice has caused a large area of upland tundra to subside, forming a shallow bowl-like depression. Numerous elongated and aligned frost scars and steps in the depression indicate movement and the frost scars are parallel with it. Above Fans D and E, the tundra mat slumps, or "flows," into the drainage area, as compared to the caving of the mat into the drainage of Fan B.

A good indicator of the age of an alluvial fan drainage area pair is the type, amount, and distribution of vegetation on the pair. Koranda (1958) studied the plant ecology of the Franklin Bluffs, and has proposed a relative age sequence for some of the fans of which Fans A, C, D, and E are included. The relative ages of A, C, D, and E as proposed by Koranda agrees with the sequence presented in this paper, but his differentiation of the fans is based primarily on ecological factors, while the stress here is on morphological characteristics and the relative degrees of mass wasting.

The extent to which a fan is covered by vegetation is a good indicator of the extent to which the fan is stabilized. As the fan becomes more stable, the vegetation cover expands and correspondingly decreases the surface area of gravel cover (Fig. 8, Plate II). The best example of the relationship of age and vegetation is found on Fan E, where a species of willow that covers the upper one-third of the fan proper also extends on up into the drainage area. It is a known fact that vegetation associations in a Tundra Climate are very closely controlled by edaphic conditions. This same species of willow, both on the fan and in the drainage area, indicates similar edaphic conditions in the two areas, and a correspondingly high degree of equilibrium. The characteristics of this fan and its drainage area indicate that they are close to being at grade.

About one-quarter mile south of Fan B, there is an example which illustrates a further step in the sequence toward grading of the fan and its drainage area. There, a very large fan was extensively truncated at some time in the past. Its sizeable drainage area allows for the accumulation of much wind-drifted snow. Thaw-produced runoff water has cut a deep, steep-sided channel

into the old fan which extends all the way to the river. The channel has been graded very similar to the channels of other streams on "old age" fans. The channel and drainage areas have an average slope of  $15^\circ$ . On the sides of the ravine, there is abundant vegetation composed of grasses, sedges, moss, and willows as much as 9 feet high. The bed load of the stream consists predominantly of boulders and cobbles, with some smaller gravels. During maximum discharge, the stream is obviously competent to transport its load to the river.

Franklin Bluffs is a unique area in which to study the development of alluvial fans and their drainage areas, since so many stages of their development are present in a very limited area. Their growth is initiated as a colluvial cone on the steep gravel bluffs. They continue to grow until a graded stage is reached. In this stage, the slope-angles of both members of the alluvial fan-drainage area pair are about equal; both members of the pair are of about the same size; there is almost no movement of material on their surfaces; and, the entire surface is well vegetated. All the features that characterize the graded slope develop in a continuum of changes which is initiated in the colluvial cone stage of the sequence.

The object of this paper has been to describe the sequential development of an alluvial fan forming in a Tundra Climate. The regime of the alluvial fan development in this environment appears to be different than the development of similar features in semi-arid regions, as described by Eckis (1928) and Blissenbach (1954). This study, like any study, has presented many additional problems that could be investigated. One of these problems would be a detailed study of the historical relationship of the Franklin Bluffs to the Sagavanirktok River. This history is well recorded by the large channel-scarred terraces, truncated and compound fans, and misfit drainage areas (large drainage areas with little or no fans). More quantitative data could be obtained from the numerous fans which feature the face of the bluffs for a length of more than 10 miles. Koranda (1958) has already conducted an extensive quantitative study of the plant ecology for one section of the bluffs, but much information on slope angles and material size distribution could be collected and analyzed.

#### ACKNOWLEDGEMENTS

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## An Unusual Case of Stream Piracy

FRANK RECKENDORF<sup>1</sup> AND KEITH M. HUSSEY<sup>1</sup>

*Abstract.* An unusual case of stream piracy took place in the recent past through the Franklin Bluffs on the Arctic Coastal Plain of Alaska. The Sagavanirktok River and Hawk Creek occupied opposite positions on the sides of a ridge, with the result of a rapid lowering of the divide between them. Loss of cementation (by thaw) of the gravels in the formation separating them continued until the higher flowing Hawk Creek burst through the ice-free gravels of the ridge to join the Sagavanirktok River about one-half mile upstream from its former junction.

An unusual case of stream piracy took place in the recent past on the Arctic Coastal Plain of Northern Alaska. It is unusual in that it could have taken place, as it did, only in an area of continuously frozen ground such as is peculiar to the high latitudes.

The piracy took place through the Franklin Bluffs; a prominent scarp along the eastern side of the Sagavanirktok River Valley between latitudes 69° 40' and 70° 00'. The bluffs form one of the most outstanding relief features on the Coastal Plain. They range up to better than 500 feet above the river at the location of Bruce Benchmark. A broad, flat upland extends eastward from the bluffs. The western slope of the upland is divided into a number of small drainage basins which drain into the Sagavanirktok. One such basin extends through the bluffs, dividing them into a Southern and a Northern Section. The break is located just north of the former junction of Hawk Creek<sup>2</sup> (Fig. 1-L) with the Sagavanirktok.

The example of piracy in question occurred near the northern

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<sup>2</sup> Proposed name for the pirated stream.