Hillslopes, Forests, and Fires in Interior Alaska

Dan Mann
Geography Program, SNRAS, UAF
dhmann@alaska.edu

INTRODUCTION

Numerous processes, both physical and biological, have interacted to create the landscapes we see today in Interior Alaska. Some of these processes are active today; others have not acted for thousands of years. Because this region is located at high latitude, environmental changes have been particularly drastic and rapid here. As a result, Interior Alaskan landscapes carry the imprint of a fascinating mixture of prehistoric and contemporary processes. Here I touch on just three: hillslope erosion, forest succession, and wildland fires. All three interact to shape the present landscape.

HILLSLOPES

The Earth's surface is a collection of slopes of varying steepness and extent. Each of these slopes represents a gradient of potential energy, and the amount and rate of erosion relates to this energy gradient. This seems straightforward; however, numerous complications arise in the form of thresholds that regulate when and how the potential energy stored on hillslopes can be released. Interior Alaska has especially interesting thresholds governing its slope processes for three reasons: 1) prehistoric climatic conditions that were quite different from today, 2) the presence of permafrost in the ground, and 3) fire-prone vegetation covering the land surface. In what follows you'll see how each of these factors influences slope processes and hence the form of the present landscape.

The Importance of Permafrost

The thawing of permafrost and the geomorphic instability it causes is probably the most important threshold response controlling hillslope erosion and hence the nature of Interior Alaska's landscape. Permafrost in Interior Alaska is discontinuous (Fig. DM-1) and its distribution on the landscape in complex. Streams and ponds are underlain by unfrozen taliks, and many south-facing slopes lack permafrost altogether. In contrast, north-facing slopes may have permafrost extending from the surface to a depth of several hundred meters or more (Fig. DM-2). The topographic complexity of ground temperature is largely the result of the low sun angle experienced at this high latitude. Because of this low sun angle (only 47 degrees above the southern horizon at the summer solstice) we live in a land of large shadows.

Permafrost in Interior Alaska is vulnerable to sudden thaw because it is relatively warm – most of it has a temperature only several degrees below freezing. The transition from ice to liquid water triggers radical changes in the physical properties of the surrounding material. Material that was locked in icy stability for millennia can suddenly find itself moving downslope in a semi-fluid state. Slope angles that were formerly equilibrated to frozen conditions suddenly find themselves oversteep and unstable. Rapid thaw can trigger landslides of various sorts, the most spectacular being retrogressive thaw slides (Burn and Lewkowicz, 1990) (Fig. DM-3). The alteration of existing topography by the melting of underlying permafrost is called thermokarsting, and the effects of this process are all around us. Prehistoric thermokarst events have left their mark on the modern landscape in the form of two very striking geomorphic features: relict rill networks on valley sides, and, at a larger spatial scale, asymmetrical valleys.

Relict Rill Networks on Loess Hillsides
Many south- and west-facing valley walls in the Fairbanks area preserve relict drainage systems consisting of dendritic networks of rills (Fig. DM-4). The rills are typically flat-floored, 3-10 m wide, and 2-8 m deep. They are incised in loess of Pleistocene age. Only rarely do these drainage networks carry overland flow of water today. Pits excavated in the bottoms of the rills reveal a meter or more of multiple buried soils marked by B horizons and layers of charcoal. Apparently, slope wash after fires has been infilling rills that were once much deeper. As you can tell from the crudeness of my illustrations, these rills have never been studied in detail. What little we know about the timing of their formation comes from the work of Tom Hamilton at the Permafrost Tunnel in Fox (Hamilton et al., 1988). Hamilton found that gullies developed along the loess-blanketed sides of the Goldstream valley 11,300-11,100 ^{14}C yr BP around the time of the Pleistocene – Holocene transition; in other words, during a time of rapid climate warming (Fig. DM-5). These gullies incised old loess deposits, creating an erosional unconformity in the loess sequence and truncating large ice wedges. Interestingly, Hamilton et al (1988) think that a similar thaw event may have occurred earlier - perhaps during the last interglacial - and created the striking unconformity seen in the permafrost tunnel between the lower and upper silt units (Fig. DM-5). The alternative is that Goldstream created this older thaw unconformity when it meandered near the tunnel site and caused thermokarsting and mass movements on the adjacent slope.

The thaw episode described by Hamilton et al. (1988) in the Permafrost Tunnel ca. 11,000 ^{14}C yr BP might explain the origin of relict rill systems throughout the region. The scenario might have been something like this: Sudden warming at the close of the ice age caused active layers to deepen on hillslopes. (The active layer is the uppermost level of a soil that freezes and thaws every year.) Deeper active layers then caused the permafrost that formerly existed as interstitial ice (e.g., ice lenses) and large ice wedges to thaw. The ground lost its previous resistance to down-slope movement, which triggered widespread solifluction and landslides. At the same time, the warming atmosphere and shrinking Bering Land Bridge probably allowed more water vapor to be transported into the region, and precipitation increased radically. Perhaps the dry summers of the ice age were suddenly replaced by a summer rain regime like we have today. The vegetation may have been highly disturbed at this point in time because it was in a state of transition between steppe-tundra and forested parkland (Higuera et al., 2009). Perhaps this disturbed vegetation cover did little to prevent soil erosion. During the ice age, the steepness of the hillslopes and the arrangement of the drainage networks must have been equilibrated to a much different vegetation cover. Slope angles, channel networks, vegetation, and soils would have all been frantically readjusting to the warmer, wetter, and woodier environment. It is also possible that wildland fires increased in frequency at this time as flammable species like shrub birch colonized the landscape. The combination of thermokarst, increased precipitation, and disturbed vegetation cover may have triggered a sudden and short-lived bout of deep erosion that cut the rill systems. As trees colonized the area in the early Holocene, the hillslopes were restabilized and the rill networks became largely relict. This scenario is obviously speculative. This topic is highly relevant to understanding the impacts of ongoing global warming in Interior Alaska and would make an excellent Masters or PhD study.

Forest Fingers: Another Undescribed Slope Pattern in Interior Alaska

A second geomorphic/vegetation pattern that is quite distinct from the relict rill networks exists on hillslopes in Interior Alaska (Fig. DM-6). These "forest fingers" are widespread on north-facing slopes between the Tanana and the Yukon River. Good examples can be seen from Dalton Highway near Grapefruit Rocks. This hillslope pattern is formed by fingers of birch and white spruce forest that radiate from hilltops downslope between corridors of black spruce muskeg. From a distance, it appears that the fingers of tall trees are actually topographically higher than the intervening muskegs, but this is an artifact of the height of the tree canopy. In fact, the closed-canopies of tall trees line drainage ways, and the muskegs occupy the interfluves (Fig. DM-7). Often these drainage ways are networks of thawed ice wedges, and the streams flow largely beneath the ground. Active layers are typically thin (10-30 cm) in the peatlands but often >1 m in the forest fingers. This difference in soil temperature and hence soil drainage seems to be the root cause of the forest finger pattern, though there are undoubtedly complex feedbacks on soil temperature caused by the vegetation cover, specifically the lack of an insulating peat cover inside the forest fingers. Like the relict rills networks, this geomorphic slope pattern has never been studied. Deciphering the key processes that control this pattern may prove valuable in helping us predict how the landscape of Interior Alaska will respond to rapid warming over the coming decades.

WILDLAND FIRES

In the boreal forest, wildland fires are important both for controlling the distribution of vegetation and for triggering hillslope erosion. You will pass through several large fires that burned this last May on the road to Manley. Here we cover some basics about fires in Interior Alaska, then talk about the vegetation mosaic, and finally return to the topic of hillslope erosion.

Alaskan Fire Basics

Interior Alaska between the Alaska and Brooks Ranges contains about 150 million burnable acres, which equates to the combined areas of Montana and Idaho. This seems like a lot of real estate until you realize that Alaska contains just 4% of the global boreal forest, a circumboreal biome that contains 1/3 of the Earth's total forest cover. The global boreal forest contains roughly 1/3 of the terrestrial carbon stored on the planet. The dynamics of this carbon (whether it is being stored or being released to the atmosphere) has the potential to affect climate worldwide. Wildland fires are the main way that carbon stored in boreal forest vegetation and soils is recycled to the atmosphere. Bottom line: fires in the boreal forest are a big deal for global change.

Boreal forest fires have several interesting traits. First of all, the big fires are almost all started by lightning. Most human-ignited fires occur along the road network and are quickly put out. On average, 840,000 acres burns in Interior Alaska every summer. Since 1950, the largest annual area burned was 6.4 million acres in 2004. It is important to remember that annual area burned follows a power law much like the frequency-magnitude relationship of earthquakes. In other words, most of the area burned does so during rare fire years. In most years, very little of the forest burns, but occasionally (as in 2004) the whole countryside seems to be on fire. There are important effects of climate seasonality on area burned. In the record years of 2004 and 2005, unusually dry periods in late summer allowed the fires that ignited in June and July to expand across huge areas by the end of September. The three biggest fire seasons during the last 60 years (1957, 2004, 2005) were among the driest Augusts on record (Fig. DM-8). In 2010, an unusually dry May saw widespread burning. This is when the Applegate (RL047) and Cascaden Ridge

(RL041) fires burned across the highway between Livengood and Manley (Fig. DM-9). Earlier and later fire seasons could be the way of the future in Interior Alaska.

Fire, Physiology, Aspect, and the Forest Mosaic

The vegetation mosaic you see on the landscape (Fig. DM-10) is the outcome of interactions between plant physiological tolerances, time-since-last-fire (TSLF), and aspect-related microclimatic conditions. In other words, the forest you see in partly the result of history (How many years has post-fire succession gone on?) and where different species are able to grow. At some sites, post-fire succession leads from deciduous herbs and shrubs to spruce trees. Then the site burns again, and succession is reset to herbs and shrubs. However, the details of this deciduous to conifer cycle vary greatly at different sites on the landscape. At extremely dry and warm sites, aspen clones typically self-replace themselves after fires by sprouting from their roots. (Fires rarely heat the soil enough to kill all the plant roots there, so root-sprouting is a widespread trait among boreal forest plants). At extremely cold and wet sites, black spruce typically self-replaces itself from seeds that it stores in serotinous cones for decades in its canopy. It is only at sites where all the different tree species are able to grow successfully that there is a progression from deciduous to conifer species during post-fire succession.

What is the relative importance of history (TSLF) versus the tree physiology-microclimate connection in determining the forest mosaic we see on the present landscape? In one study done near Fairbanks (Kurkowski et al., 2008), it was estimated that 70% of forest stands had their species compositions predetermined by the self-replacement of the pre-fire dominant species. Remember that the ability to self-replace is determined by the combination of site microclimate (determined by elevation, slope, and aspect) and the tree species' physiological tolerances. The other 30% of stands may have been stages in the deciduous to conifer successional sequence. The take-home lesson is that the striking forest mosaic you see on the landscape north of Fairbanks is the combined result of interactions between plant physiological tolerances, time-since-last-fire (TSLF), and aspect-related microclimatic conditions.

Fires, Thermokarst, and Landscape

Fires cause influence hillslopes and hence the form of the landscape in two ways. First they remove vegetation that stabilizes the soil. It is well known in the Lower 48 that fires trigger huge increases in slope erosion by removing vegetation (Moody and Kinner, 2006). Second, and most importantly in our region, fires trigger thermokarst by causing the thawing of underlying permafrost (Fig. DM-13). Little of this thawing occurs from direct heating because fires are very short-lived. Instead fires trigger permafrost mainly by removing the organic material that formerly insulated the ground (Osterkamp et al., 2000; Jorgenson and Osterkamp, 2005; Liljedahl et al., 2007). Post-fire erosion has never been systematically studied on Alaskan hillslopes, but the effects of fire here are probably much greater than in the Lower 48 due to the involvement of thermokarst. Figure DM-11 is a photograph taken last month at the site of the Anaktuvuk River fire that occurred in 2007. By removing 5-20 cm of peat from the ground surface, this fire in tundra triggered numerous thermokarst mass movements. Much of the present landscape of Interior Alaska has been shaped by the combined effects of fires, thawing of permafrost, and mass movement.

A NOTE ON HILLSLOPES AND MEGAFAUNA BONES

Alaska contains a unique archive of the remains of extinct animals. The most spectacular of these animals are megafauna (animals >70 kg) that lived here when the region was part of the circumboreal mammoth steppe (Guthrie, 1990). We owe the preservation of many of these bones to hillslope processes.

Bones don't last long on the ground surface, even in the Subarctic. Lying on the surface, bones are subjected to freeze-thaw action, gnawing by mineral-hungry animals, and leaching by organic acids. Even in this cold region, bones need to be buried in order to survive. The good news for bones in a permafrost environment is that once they are buried and safely interred in permafrost, they can be preserved for a very long time.

So how do bones get safely incorporated in permafrost? There seem to be two main ways. The first is mass movement: the downslope movement of masses of unconsolidated material. In Alaska, most of this unconsolidated material is loess-derived silt. A freshly dead animal can occasionally be buried underneath a mass movement triggered by thermokarst. This is the taphonomic setting that Dale Guthrie ascribes to Blue Babe, a *Bison* mummy dating to 36,000 ^{14}C yr BP (Fig. DM-12). The second way is burial of bones by stream sediment. These two processes are closely interrelated because mass movements often transport bones downslope into floodplains where bones are reworked and the redeposited in fluvial terraces, which is how bones often end up in association with gold.

References Cited:

Brown, Jerry, and Kreig, R.A., 1983, Guidebook to permafrost and related features along the Elliott and Dalton Highways, Fox to Prudhoe Bay, Alaska: Alaska Division of Geological & Geophysical Surveys Guidebook 4, 230 p.

Burn, C. R., Lewkowicz, A. G. (1990). Retrogressive thaw slumps. The Canadian Geographer, 34: 273-276.

Guthrie, R.D. (1990). Frozen Fauna of the Mammoth Steppe. University of Chicago Press.

Higuera, P.E., Brubaker, L.B., Anderson, P.M., Hu, F.S., Brown, T.A. (2009). Vegetation mediated the impacts of postglacial climate change on fire regimes in the south-central Brooks Range, Alaska. Ecol Monographs 79: 201-219.

Jorgenson, M.T. and Osterkamp, T.E. (2005). Response of boreal ecosystems to varying modes of permafrost degradation. Can J For Res 35: 2100-2111.

Kurkowski, T.A., Mann, D.H., Rupp, T.S., and Verbyla, D.L. (2008). Relative Importance of Different Secondary Successional Pathways in the Alaskan Boreal Forest. Canadian Journal of Forest Research 38, 1911-1923.

Liljedahl, A., Hinzman, L., Busey, R., Yoshikawa, K., 2007. Physical short-term changes after a tussock tundra fire, Seward Peninsula, Alaska. Journal of Geophysical Research, 112, (F2): F02S07 doi:10.1029/2006JF000554.

Moody, J. A., and Kinner, David A., 2006, Spatial structures of stream and hillslope drainage networks following gully erosion after wildfire: Earth Surface Processes and Landforms, v. 31, no. 3, p. 319-337.

Osterkamp, T. E., Jorgenson, M. T., Schuur, E. A. G., Shur, Y. L., Kanevskiy, M. Z., Vogel, J. G., Tumskoy, V. E., 2009. Physical and ecological changes associated with warming permafrost and thermokarst in Interior Alaska. Permafrost and Periglacial Processes, 20 (3) 235-256.

FIGURES

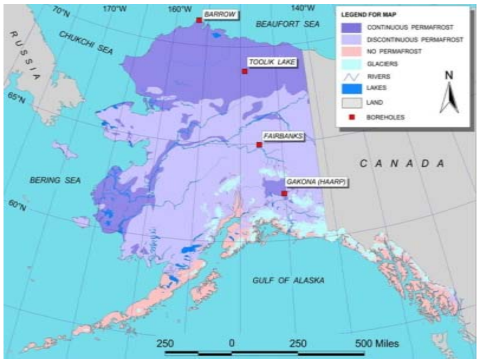

Figure DM-1. Permafrost map of Alaska (UAF Permafrost Lab, V. Romanovsky). Note the patchy distribution of continuous permafrost south of the Brooks Range. The distribution of permafrost in Interior Alaska is discontinuous and complexly interrelated to topography and geomorphic history. Why is permafrost continuous on the Y-K delta and along the lower Yukon River?

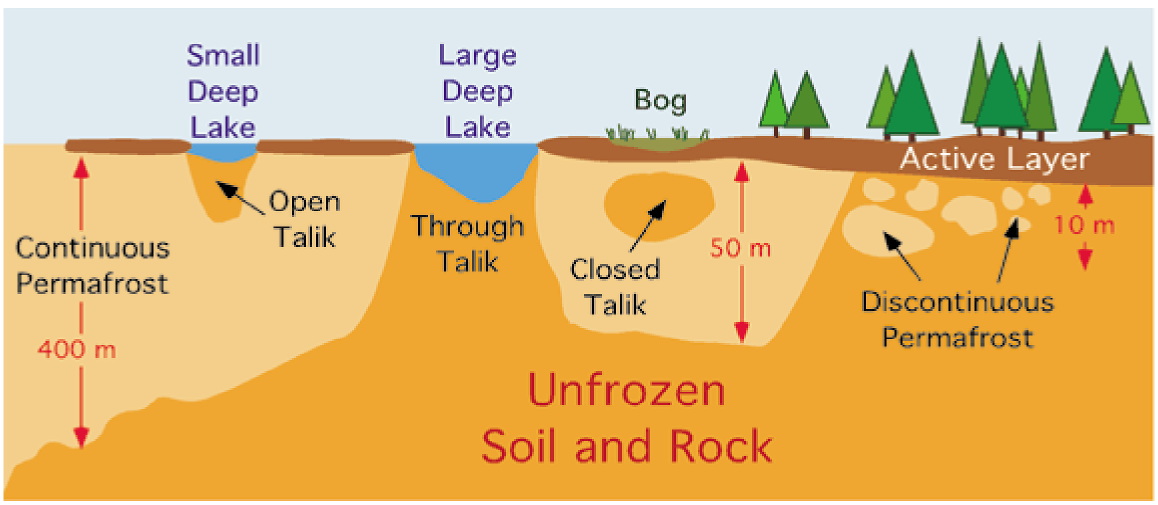

Figure DM-2. Cross section of the transition zone between continuous and discontinuous permafrost. Shown are various types of talik or unfrozen ground. An "open talik" is an area of unfrozen ground that is open to the ground surface but otherwise enclosed in permafrost. A "through talik" is unfrozen ground that is exposed to the ground surface and to a larger mass of unfrozen ground beneath it. Unfrozen ground encased in permafrost is known as a "closed talik." *Note that the active layer (the near-surface layer that freezes and thaws every year) should be shown as much thinner in the peat bog.* (graphic from Encyclopedia of the Earth).

Figure DM-3. Retrogressive thaw slide along Itillyargiok Creek in central Brooks Range, July, 2010. Creek in foreground is 4 m across. Once thawing begins, removal of insulating vegetation and peat causes permafrost to thaw faster, which sustains a positive feedback that can continue for years and cause mass movements of millions of tons of material downslope.

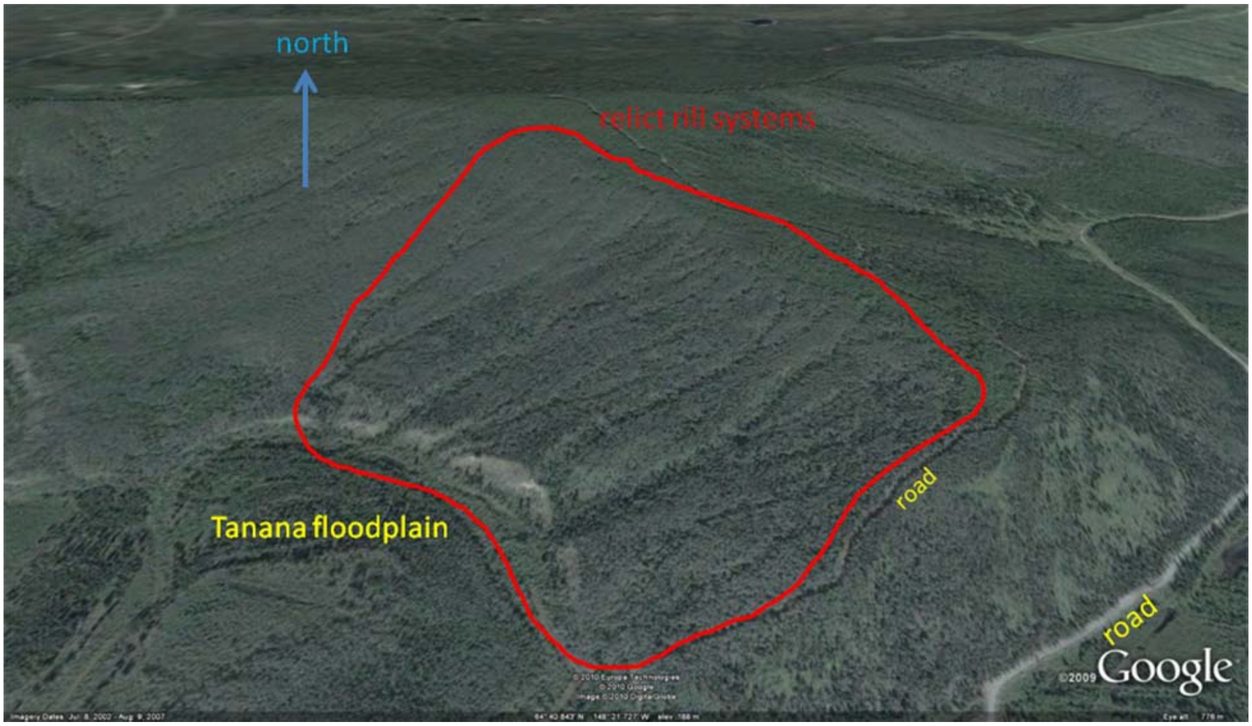

Figure DM-4. Oblique view of a west-facing hillside near Bonanza Creek along the Tanana showing abandoned rill systems. The road in the lower right is approximately 10 m wide. White spruce and birch grow in bottoms of rills, and aspen grow on drier interfluves. Similar relict drainage networks are common on loess-blanketed slopes in Interior Alaska. They probably date to the early Holocene.

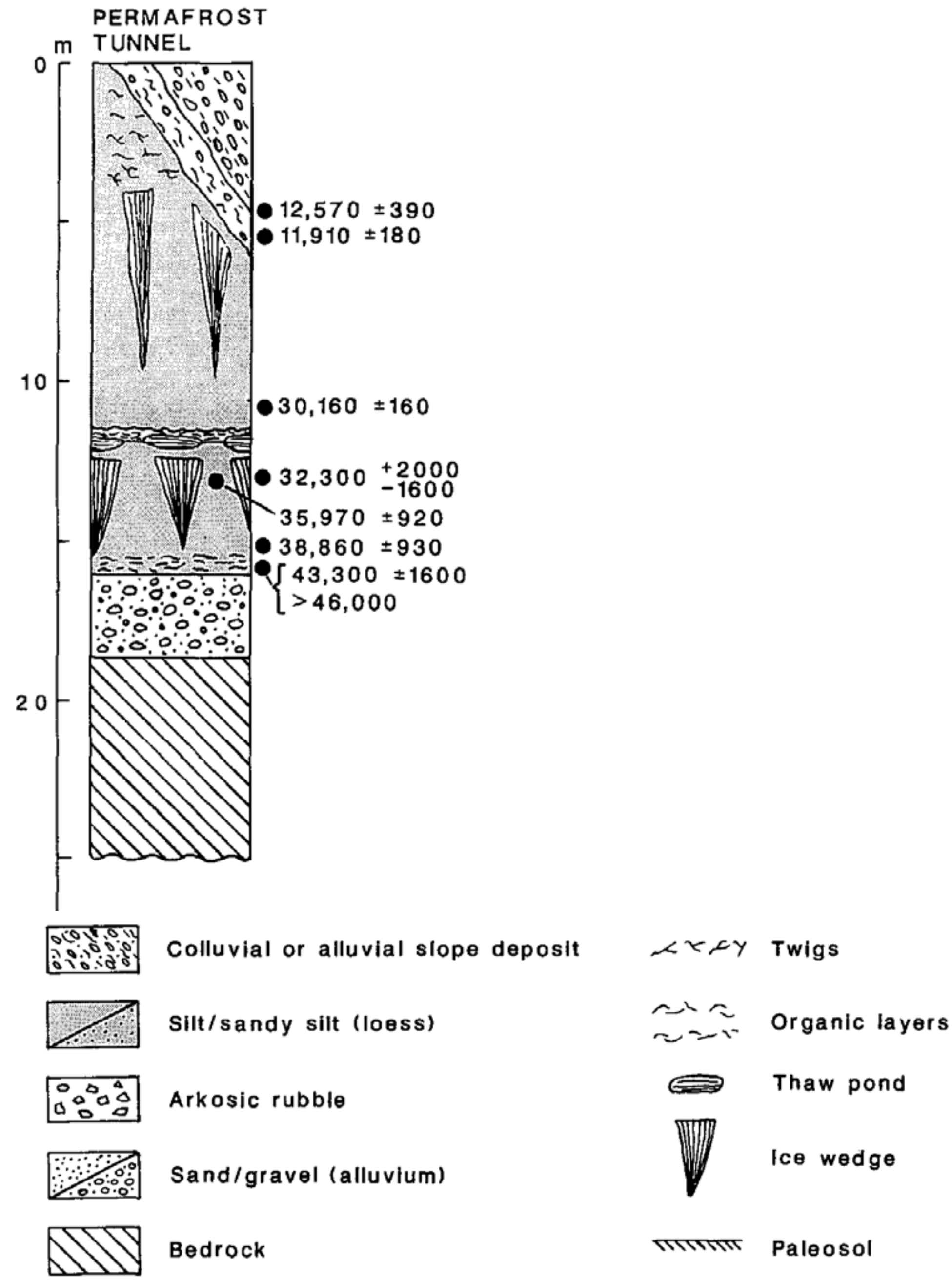

Figure DM-5. Stratigraphy near the entrance of the Permafrost Tunnel at Fox showing the erosional unconformity related to a major thaw episode that occurred during the Pleistocene/Holocene transition. This same warming event may have caused rill formation on loess slopes throughout the region. An older thaw event occurring ca. 30,000 ^{14}C yr BP probably truncated the lower band of ice wedges. From Fig. 17 of Hamilton et al. (1988).

Figure DM-6. Tree fingers on a north-facing slope in the Chatanika valley. Bands of birch and white spruce line drainage ways that radiate from ridge crests. The river is approximately 30 m wide here. White lines in valley bottoms are aufeis. The vertical relief here is about 100 m.

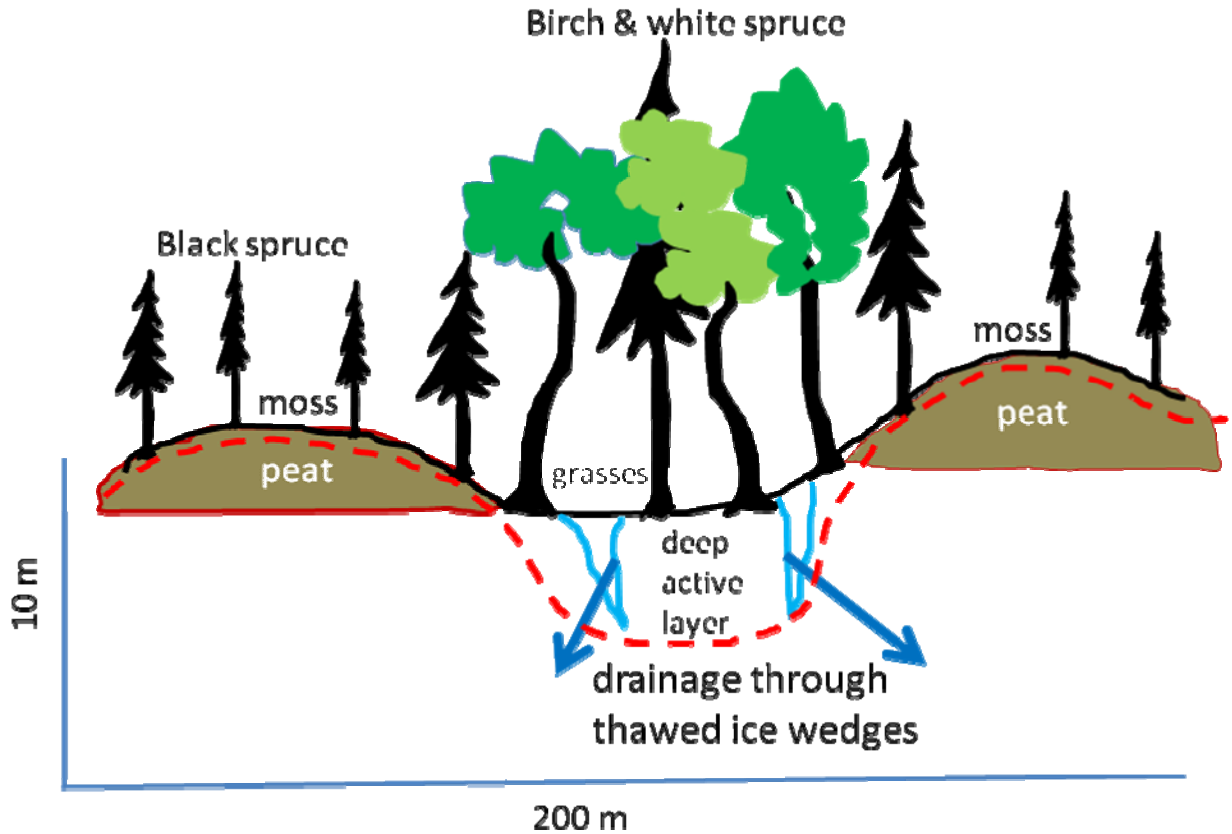

Figure DM-7. Schematic cross section of a forest finger. Drawing is oriented across the slope. The dashed red line is the base of the active layer in late summer. The tree fingers occupy slight topographic depression that run downslope and carry small streams that often flow partly underground through systems of thawing ice wedges. This interpretation is based on only a few hours of field work.

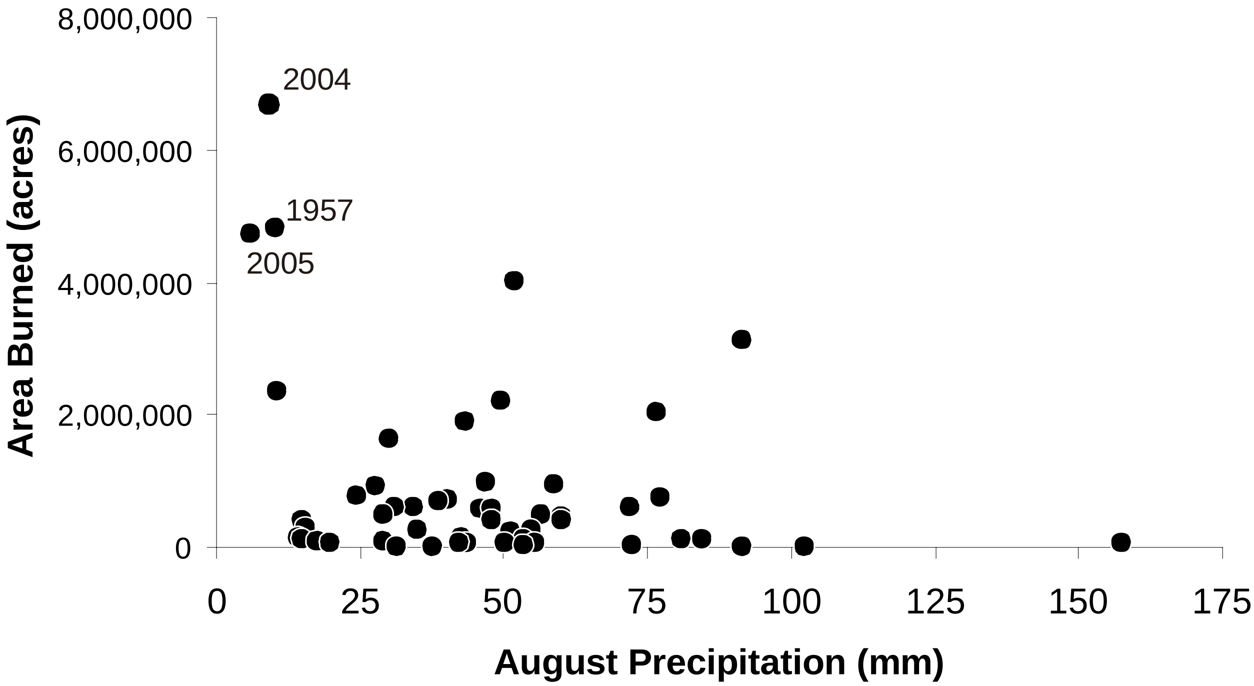

Figure DM-8. Area burned in Alaska between 1956 and 2006 in relation to August precipitation at Fairbanks in the same years (BLM Large Fire Database). The three summers with the largest area burned had the driest Augusts on record. Annual area burned is tightly controlled by summer climate conditions.

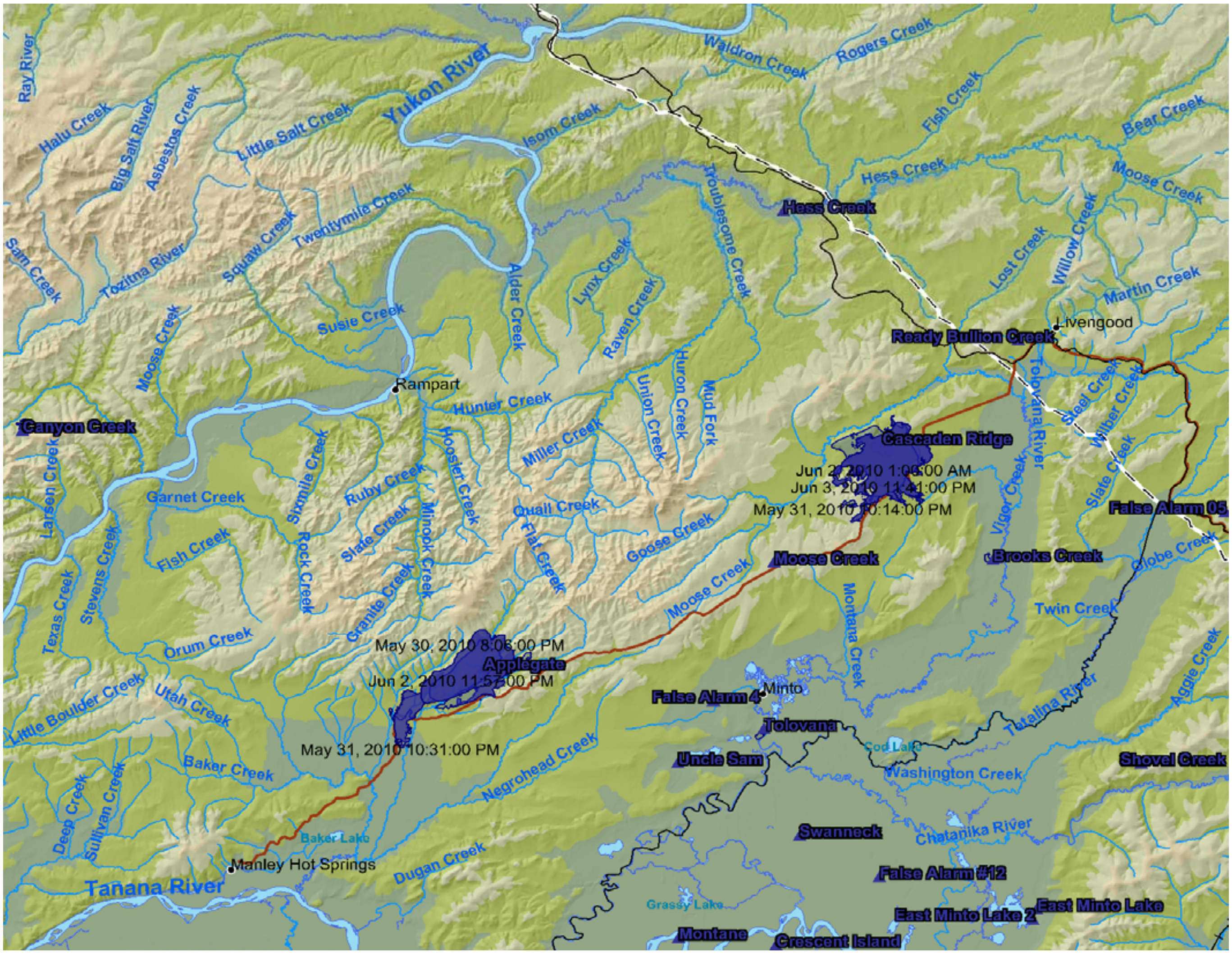

Figure DM-9. Fires that burned in May 2010 in the Livengood-Manley area. Other fires that were ignited but failed to spread (or were extinguished) are shown in purple. All these fires were started by lightning. From the BLM Alaska Fire Service website at http://afsmaps.blm.gov/imf/imf.jsp?site=firehistory. The Yukon Tanana Uplands is covered by a complex mosaic of overlapping burns of different ages.

Figure DM-10. The complex mosaic of forest cover is created by a combination of historical effects (time- since- last- fire) and by interactions between microclimatic gradients set up by the low summer sun angle and the physiological tolerances of different plant species. Black spruce typically self-replaces itself after fires at cold, moist, north-facing sites. Aspen self-replaces itself at warm, south-facing sites. On the north side of Ester Dome where this photo was taken, approximately 70% of forest stands grow where they do because of microclimate-physiological reasons, not because of time-since-last-fire (Kurkowski et al., 2008).

Figure DM-11. Retrogressive thaw slides triggered by thawing of permafrost after the 2007 Anaktuvuk River fire on the North Slope. Note the blue and white helicopter for scale. These landslides were probably triggered by the deepening active layer that resulted from the combustion of 5-20 cm of insulating peat. Similar mass movements are common in the boreal forest after fires and have probably played an important role in shaping the geomorphology of the Yukon Tanana Upland. This photograph taken on July 20, 2010.

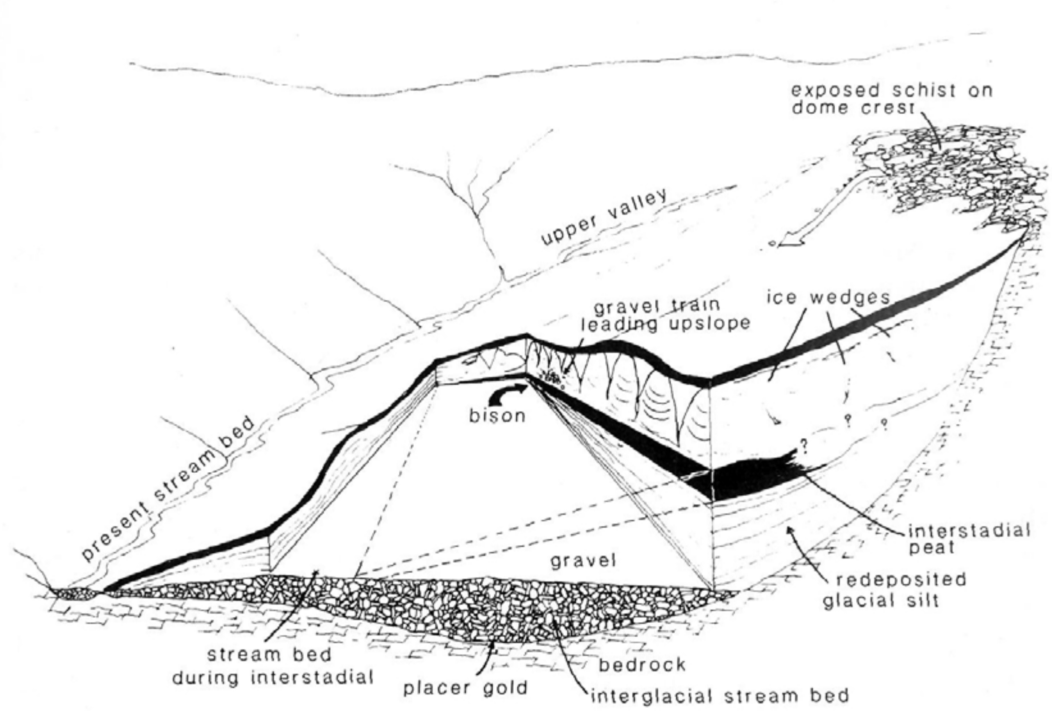

Fig. 2.13. Diagrammatic Pearl Creek section drawing. Gravels exposed at the Pearl Creek mine are portrayed as the former bench of a stream that has migrated and is now stabilized against the opposite valley wall. The fossil side "stream" which brought bedrock material down from the hill crests is also shown. Transport of schist downslope indicates rapid water runoff also capable of carrying enough silt to cover Blue Babe.

Figure DM-12. Guthrie's sketch of the stratigraphic setting of Blue Babe, the 30,000-year old *Bison priscus* mummy. His idea is that the recently killed bison was buried under a landslide of redeposited loess. This landslide was probably triggered by melting permafrost. Once interred in permafrost, megafauna bones can be reworked downslope during successive thaw episodes until they end up in the stream bed and eventually are concentrated in stream terrace deposits. Most bones are never buried in the first place. This taphonomic hypothesis suggests that bone preservation occurs most often during periods of rapid climate warming.

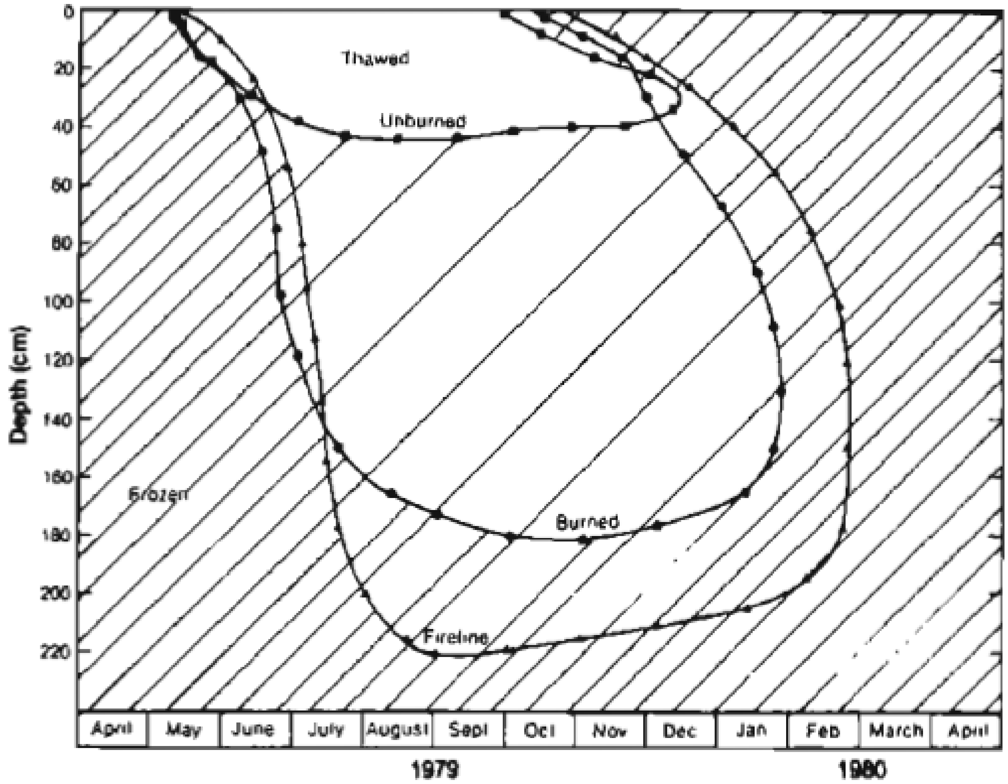

Figure 28. Time and depth of freeze and thaw for the unburned control, fireline, and burned black-spruce stand for the period April 1979 through March 1980 as determined by probing and by soil temperature measurements (from Viereck, 1982, fig. 11).

Figure DM-13. Figure from Vierick's contribution to Guidebook to Permafrost and Related Features along the Elliott and Dalton Highways, Fox to Prudhoe Bay, Alaska, 1983.