

# Ice wedges of the Dalton Highway, Alaska

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North America's largest oilfield was discovered in 1968 at Prudhoe Bay; it contained over ten billion barrels of recoverable oil about 3000 m beneath the Arctic Coastal Plain. Its development changed Alaska's economy for ever, and included building the oil pipeline from Prudhoe Bay to Valdez. The haul road alongside the pipeline is still the only road across northern Alaska, and was named the Dalton Highway when it was opened to public access. It crosses the wilderness of the Brooks Range (Fig. 1), and allows completion of a north-south traverse of Alaska, across a broad range of geology and geomorphology; it was the destination for a Geologists' Association field trip in 1999, when these notes were compiled.



Fig. 1. A truck on the Dalton Highway across soliflucted slopes north of the Atigun Pass over the Brooks Range.

The two great mountain ranges of Alaska, the Alaska Range in the south and the Brooks Range in the north (Fig. 2), are accumulations of accreted terranes on the convergent plate margins of the Pacific and Arctic Oceans respectively, and both developed major icecaps during the Pleistocene; large glaciers are still fed by Pacific-derived rainfalls on the Alaska Range, but there is none today on the drier Brooks. The intervening Yukon valley and the Arctic Coastal Plain are cold deserts in the mountain rain shadows; they are classic periglacial environments (Ferrians 1994). Their total lack of glaciation throughout the Pleistocene is perhaps most famed for the consequent survival of many rich

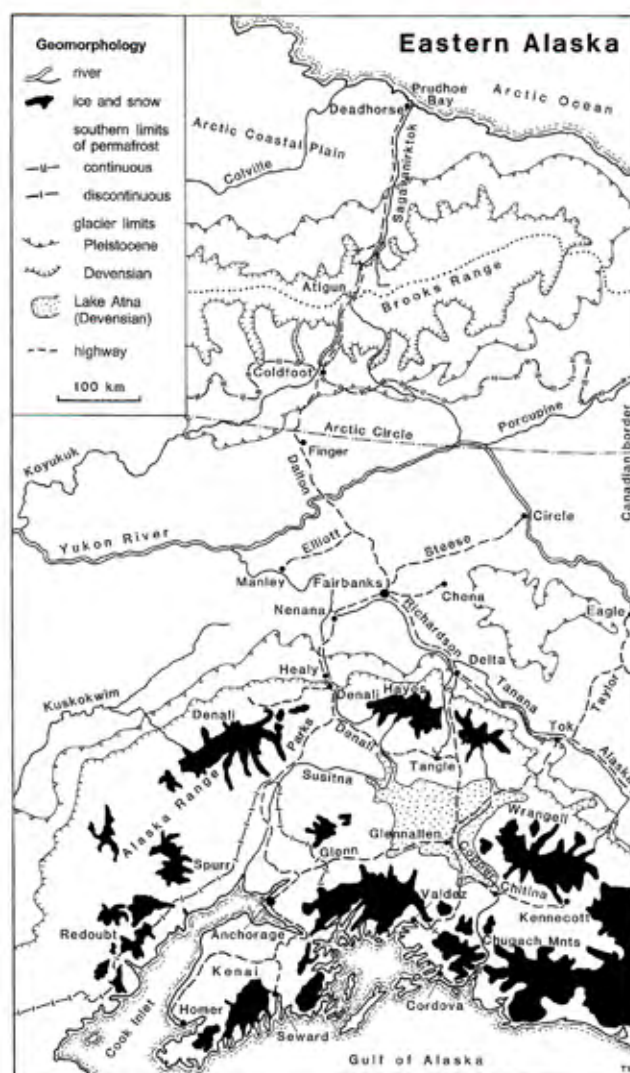


Fig. 2. Major geomorphological features across Alaska.



placer gold deposits, notably in the Klondike valley, just over the border in Canada (Waltham 1995).

Permanently frozen ground develops where all the groundwater freezes due to the cooling effect of the air. Continuous permafrost occurs where the mean annual air temperature is lower than about  $-8^{\circ}\text{C}$ ; this pertains on the Arctic Coastal Plain and over the higher mountain areas. The permafrost depth is determined by the balance between surface cooling from above and geothermal warming from below. Around Fairbanks it is about 20 m deep (and discontinuous), but it deepens to 100 m on the rise to the Brooks Range, and is 600 m deep under Prudhoe Bay, before it reduces to 300 m under the waters of the Arctic Ocean. This may be compared with the estimated depths of permafrost in England during the Pleistocene ice maxima, that increased from about 50 m near the south coast to around 200 m in the Humber/Tees area (Hutchinson 1991; Higginbottom & Fookes 1970).

Discontinuous permafrost occurs where mean air temperatures are  $-1^{\circ}$  to  $-8^{\circ}\text{C}$ , and this applies across the interior Yukon valley. It has very patchy distribution, and is normally absent under rivers and lakes; under hillsides it varies in thickness with aspect to the sun. The climax vegetation is taiga on the discontinuous permafrost, and is tundra on the continuous.

In summer, solar radiation thaws the ground ice nearest to the surface; this is the active layer of annual freezing and melting, and is normally 1–3 m thick above the permafrost table. Soils and sediments within the active layer become saturated, undrained and unstable in the Arctic summers. Gravels that retain grain-to-grain contact are thaw-stable; clays and silts are solid when frozen, but are very weak when wet and saturated; sands are thaw stable with a low ice content, but some permafrost contains over 60% ice, and this collapses when it is thawed.

## Construction on the permafrost

Conservation of the ground ice is the key to successful construction (McFadden & Bennett 1991). Roads rest on thick gravel pads, that may be built with internal air ducts for extra cooling. Small buildings are elevated on wooden blocks, and larger structures stand on adfreeze piles; these are frozen into the permafrost by a slurry placed around a steel pile in an over-bored hole.

The Trans-Alaska Oil Pipeline is the world's largest structure built on permafrost (Godfrey 1978; Luscher *et al.* 1975). Heat from the flowing oil in an uninsulated buried line would create a thaw zone some 20 m deep and wide after 30 years; this would be a saturated bog in thaw-unstable soils. Consequently, the pipeline is elevated on piled trestles for 611 km (Fig. 3): hollow steel piles reach 5–20 m down into permafrost beneath the active layer. To conserve the permafrost, each pile



Fig. 3. The oil pipeline elevated on its trestles with the cooling fins rising from the tops of the refrigerated piles into the permafrost.

has its own internal, self-operating refrigeration system so that it remains frozen into the ground ice; internal tubes carry circulating ammonia, which rises as a warmed gas into heat-dissipating fins on top, and in winter sinks as a cooled liquid back into the buried section of the pile. With trestles at 18 m centres, 78 000 piles were required, and 61 000 of these have the internal refrigerators. Most of the remaining 666 km of the pipeline is buried in thaw-stable rock or gravel, and also in the unfrozen ground beneath rivers and south of the Alaska Range; 11 km of the pipeline is buried in artificially frozen trenches through sensitive areas.

## The Dalton Highway

From Fairbanks to Prudhoe Bay is almost exactly 800 km, first along the old Elliott Highway, and then along the Dalton, practically all of it alongside the oil pipeline. The 580 km north of the Yukon River was built in the single summer of 1974, working on seven spreads from construction camps that were supplied through their own airstrips (McPhail *et al.* 1976). Most of the roadbed was formed by end-tipping  $18 \text{ Mm}^3$  of gravel that was taken from quarries and a few deep cuts. This method displaced the thin layer of thawed muskeg to create a stable insulating mat on the permafrost; frozen ground was by then understood well enough to avoid the desparate chaos that was created by building the Alaska Highway 30 years previously.



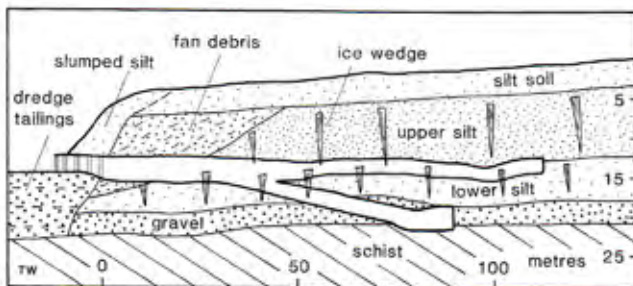


Fig. 4. Simplified profile of the Fox tunnel; vertical scale exaggeration is 2.



Fig. 5. The arched roof of frozen silt in the Fox tunnel.

The road traverses a variety of geology that is mostly poorly exposed, and also reveals a host of geomorphological features (Brown & Krieg 1983; ANHA 1993; Waltham 1999). Ground ice was encountered in many of the new roadcuts, but the exposed faces soon thawed; the soil cover has slumped over them, so that today the summer traveller sees no ice unless he searches for it.

### The Fox permafrost tunnel

During the 1960s an experimental tunnel was driven into the side of the Goldstream Valley at Fox, 10 km north of Fairbanks, to investigate stability in the frozen ground. It heads into a low bluff of frozen soil that was left at the margin of massive dredged workings for placer gold. The Elliott Highway lies on the dredged ground, just in front of the tunnel mouth, which lies in a fenced compound screened by young birch and alder scrub.

The tunnel is 110 m long, with a descending branch that is 40 m long (Fig. 4). It is 2–3 m high and 4–6 m wide (Fig. 5), and mostly lies 10–12 m below the surface. The portal is refrigerated through the unstable active layer in slumped silt, but the rest is in naturally frozen ground at a temperature of about  $-3^{\circ}\text{C}$ . The main gallery passes through a fan of slope debris into frozen silts, that are fluvially reworked loess and include some sand and gravel bars. These silts form two depositional



Fig. 6. Lines of silt, revealed by ablation, mark the internal banding that tapers downwards within an ice wedge exposed in the Fox tunnel; deep ablation scallops have silt on their floors and ice crystals on some roofs.

units, separated by an erosion surface with soil remnants that lies at the level of the main gallery. Plant roots at this horizon, along with horns and jawbones of bison, are exposed in the tunnel roof. The branch gallery descends into the gold bearing gravels, and exposes schist bedrock in its floor.

Each silt unit has its own generation of ice wedges, that date from about 40 ka and 30 ka (Hamilton *et al.* 1988). They are now stable where they are preserved in the frozen ground, though their exposed faces within the tunnel have suffered some ablational retreat and aeolian scalloping. Five wedges in the lower silt are the best exposed and are each 3–4 m deep and 1–2 m wide at the tops. Their ice has vertical banding formed by the annual increments of blown snow, dust and meltwater in the fissures in soil undergoing active thermal contraction; the bands taper downwards with the wedge profile (Fig. 6). The tops of some wedges are seen to have been truncated or slightly dished by meltwater erosion. No clear pattern of the wedges is recognizable from the restricted tunnel exposure, but a widening of one may represent a triple junction within a polygonal wedge net. A few wedges in the upper silt are seen as thin ice veins in the tunnel roof.

Horizontal ice lenses exposed in the tunnel are up to 6 m long and 1.5 m thick (Fig. 7). They represent seasonal thaw ponds that were frozen in a winter and then rapidly buried by silt deep enough to insulate them from further thaw. They overlie many of the truncated ice wedges.

Creep of the unsupported frozen ground causes convergence of the tunnel's roof and floor by about 1 mm per month; the rate increases with wider spans and higher temperatures (Huang *et al.* 1986). The only roof falls have occurred where spans of frozen silt are wider than about 10 m. Gold-bearing gravels in the lower tunnel have an unconfined compressive strength of around 20 MPa while they remain frozen.





Fig. 7. A horizontal lens of clear water ice, exposed in a wall of the Fox tunnel.

### Polygonal ice wedges in the Arctic Coastal Plain

Perhaps the most widespread landform of the Arctic Coastal Plain is polygonal ground created by nets of ice wedges (Lachenbruch 1962); these polygonal nets characterize periglacial lowlands, and East Anglia has many that are relics from the Pleistocene. Typical polygons are 15–75 m across, bounded by almost straight ice wedges each 10–40 m long between three- or four-point junctions. A uniform distribution of ice wedges creates polygons that tend to hexagonal; some nets are more rectilinear, where one set of wedges forms along fluvial channel features within the sediment, with another set at right angles.

Many polygons have no surface expression where they are stable or growing slowly in undisturbed frozen ground. Others are visible as slight ridges or vegetational contrasts over growing ice wedges. Polygons are most conspicuous where their ice wedges are thawing, to create meltwater troughs over them, and this style is almost ubiquitous alongside river channels and thaw lakes.

Any slight melting of the permafrost creates a hollow that then fills with water. Above a certain size and depth, a lake's deeper waters survive the winter unfrozen beneath a protective ice sheet, and it expands every summer when its relatively warm water degrades its shoreline ground ice. The numerous thaw lakes in the Prudhoe Bay oilfield range are characterized by long axes perpendicular to the dominant summer winds, as bank retreat by wave action and thermal erosion is more rapid where the wind is parallel to the shore. They range from tens of metres to a few kilometres long, and are constantly evolving as they migrate, enlarge, drain, coalesce and reform. As choked lakes shrink in size, the ground beneath them freezes, and this commonly initiates growth of a pingo.

Most thaw lakes are rimmed with wide zones of hummocky ground (Fig. 8) created by total collapse of



Fig. 8. A polygonal net of ice wedges has melted and collapsed along the shore of Lake Colleen at Prudhoe Bay; oilfield well housings line the horizon.



Fig. 9. Linear pools lie over ice wedges that have partly melted by late summer; the polygonal net of wedges is continuous, and they remain frozen underneath the gravel pad of an oilfield contractor's facility at Prudhoe Bay.

the ice wedges that melt in contact with the warm lake water. Away from the lakes, the wedges are seen as nets of narrow ditches. These are intrinsically more stable, and gravel pads are safely placed over them to support oilfield structures (Fig. 9).

Rapid melting of ice wedges can be seen at Mile 317 on the Dalton Highway, 150 km south of Prudhoe Bay. A culvert beneath the road carries drainage from a small catchment, and its exit creates an artificially large point flow of summer meltwater onto the permafrost. For some years this relatively warm water has been melting the ice wedges beneath a flat area of peat soils where it is almost ponded, before it flows away to the north. Summer water levels stand about 2 m below the level of the frozen ground; each ice wedge is melted back at that level, to form a cave, that then collapses to create a gully. The network of ice wedges is thereby revealed (Fig. 10).

In the late summer of 1999, the whole length of one ice wedge had melted back into a cave that could be entered



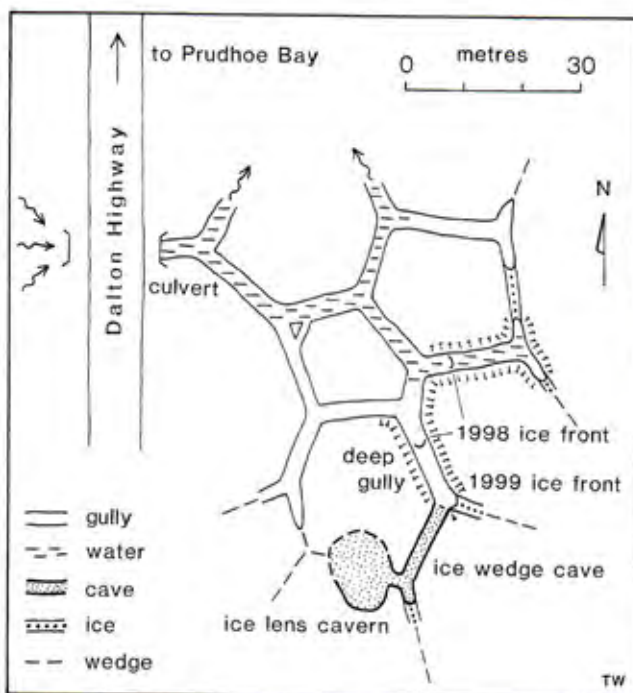


Fig. 10. Sketch map of partially melted ice wedge polygons beside the Dalton Highway; the scale is approximate.



Fig. 11. Entrance to the ice wedge cave in 1999; the wedge in the right foreground is totally melted and collapsed, while another wedge left at the polygon node remains intact.

at one end (Fig. 11). The cave was 2.5 m wide, with walls of peat, and was the width of the wedge; its roof was ice that survived above water level and was slowly wasting by ablation, as shown by its large aeolian scallops (Fig. 12). The floor of peat, mud and slush obscured any ice that survives below. The cave could be followed to a triple junction of ice wedges, where ice was undisturbed behind a scalloped face in the southern wedge. The wedge to the west opened into a wide cavern (Fig. 10). About 10 m wide, with a roof of barely frozen peat muck, this appeared to be close to collapse, and its exploration was therefore minimal. No ice was visible in its walls, and any continuation of the wedge was lost behind piles of fallen peat. The cavern has formed by the



Fig. 12. Inside the ice wedge cave; a thin roof of scalloped ice is all that remains of the upper wedge, arching between walls of peat.

total melting of an ice lens, similar to those seen in the Fox tunnel (Fig. 7), that had been buried by peat overgrowth. Its position on a wedge line suggests that the original pond started life over a partially melted ice wedge and then widened by thermal erosion of the high ground ice content of the peat bog.

These caves and the cavern will almost certainly collapse during the summer of 2000, but new ones will probably follow in the same season. A smaller cave that was accessible in 1998 had collapsed into a gully that had no exposed ice by the next summer (Fig. 10). The net of melted polygons will continue to expand until the collapsed peat prevents the culvert water reaching further ice wedges; until this happens the site is an unusual expression of permafrost geomorphology.

## Post-construction engineering

The oil pipeline has required very little modification. At Mile 211, north of Coldfoot, the pipeline loops over a hillside on new piled trestles. It had been buried in unfrozen gravels beneath the upper Koyukuk River, but subsided (without leaking) and was therefore rebuilt in 1986.

The road appears to have performed well, and its impact on the environment is minimal to the eyes of the traveller. Cut slopes were initially unstable and unsightly as the frozen ground thawed and collapsed, but after about five seasons the slopes had slumped to stable profiles with established vegetation, and the permafrost was preserved behind the new organic mat. As experience develops, most modifications to the road have been modest drainage features to eliminate winter accumulations of ice. At Mile 200, just north of Coldfoot, the road crosses a slope of frozen soliflucted till. Concentrated flows of warm meltwater emerging from culverts under the road were melting the ground ice and permitting stream scour of the downstream channels.





Fig. 13. Plastic culverts carry warm drainage clear of the Dalton Highway where it crosses a slope of frozen till near Coldfoot.



Fig. 14. Cracks in the shoulders of the highway across the Arctic Coastal Plain, where the thin edges of the gravel base are disturbed by frost heave.

Headward erosion was then threatening the road. The simple remedy was to install plastic channelling to keep the water off the permafrost until it is well clear of the road (Fig. 13). A more widespread problem is cracking of the highway shoulders (Fig. 14) where they have settled and heaved over the active ground that still thaws and freezes beneath the tapered edges of the roadbed gravel.

Greater changes through the years are seen within the oilfields themselves. Of note are the much reduced sizes of new gravel pads that support wellhead structures on the frozen tundra. The new Badami satellite oilfield has no permanent road access; both the field structures and its pipeline were entirely built from ice roads that are spray-formed on the tundra in winter and melt to leave no trace in the summer. Overland travel is still possible

on winter ice, but Badami can only be reached by air during the summer. Conservation of the permafrost and of the environment go together in impressive style on Alaska's Arctic Coastal Plain.

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