Although frozen soil provides excellent bearing for a structure, its strength properties are greatly reduced with increases in temperature and, if thawed, may be lost to such an extent that it will not support even light loads" (Dunn, 1973)

Why is this so, and what are the implications for economic development in the Arctic, in a warming world?

The historical roots of geocryology or permafrost science, according to French (2008), lie in the vast sub-arctic regions of North America and Eurasia where, as early as 1816, a pioneering logic had begun to formulate in which 'the peculiarities of the frozen ground' were seen as detrimental to economic development. Chu Pey-Yi (2011) traces this economic logic more acutely to the establishment of the USSR in 1922 as a command economy that 'effectively institutionalised the study of permafrost within a central, scientific administration.' Bent on modernising the Siberian interior and its vast, natural resource base, the geocryology that emerged was concerned primarily with the thermal interactions between the terrain and climate (ground-atmosphere dynamics) and the mechanical effects of these upon human infrastructure. Fundamentally, that same logic - though now spurned by a capitalist political economy - underlies much of the current, post-Cold war discourse on Arctic development.

In the face of climate change and with the prospects of a more accessible but equally more dangerous hinterland, permafrost studies on both sides of the Atlantic have fixated on the infrastructural - and by connotation economic and geopolitical - future of the Arctic; for instance, a recent simulation from the US National Centre for Atmospheric Research (NCAR) suggests that 'half of the area covered by the upper 3-4m of permafrost ("the discontinuous latitudes") could thaw by 2050 and as much as 90% by 2100.' Iterating the political significance and immediacy of the problem the paper concludes: '[throughout] Northern Canada, Alaska, Greenland and northern Scandinavia, the potential for damage and failure en masse of key economic infrastructure such as the oil and mining industrial complex is increasingly likely', particularly under the IPCC "business-as-usual" scenario of greenhouse gas emissions. (Ironically of course, the industrial complex contributes to this very scenario but, as Smith (2001) suggests, for the modern nation-state economic logics supersede the environmental.)

Fundamentally this essay locates within current, Arctic discourse(s) and uses "thermokarst" - the irregular, hummocky terrain characterised by instability, subsidence, erosion and local or widespread collapse - as its major unit of analysis. Primarily, I explore the development of thermokarst as 'due primarily to the disruption of the thermal equilibrium of the permafrost consequent upon an increase in surface temperature and a corresponding increase in the depth of the active layer' (French, 2009). Here, causes of the disequilibrium can be delineated between geomorphic, vegetational, climatic and human with each expressing differential effects upon the bearing capacity, lithology and structure of the terrain through the mechanics of frost heave and thaw weakening, ice expansion and pore water pressure changes. I further differentiate the causes by their scale and temporalities, for instance climatic amelioration has global, latitudinal effects on permafrost - through thaw weakening - with a relatively slow onset whilst deforestation or disruption of the surface vegetation by infrastructural engineers has a local and fairly rapid effect.

This enmeshing of scales in consequence, I suggest creates a capillary system of scalar politics - involving many state and private, distant and indigenous actors - that effectively complicates resource and land use planning, environmental risk management and civil engineering in the Arctic. Drawing upon Latour's (1994) 'actor network theory' and empirical research from Siberia and northern Canada, the latter part of this essay explores the deeply intertwined and embedded relationship between human (infrastructure/political economy) and non-human ('frozen ground'/natural resources) structures in the Arctic. Here, a comparison of the different, experiential outcomes of permafrost degradation between two localities - Canada, Northern Manitoba and Siberia, Norilsk - reveal that: (i) infrastructures of health (municipal services, water-supply, sewage treatment) and wealth (transportation links, pipelines, mining complexes) are deeply affected by the 'frozen ground' and its changing physiography and (ii) such consequences of permafrost degradation are themselves conditioned by these local infrastructures (for Norilsk, poor construction in a crumbling Soviet economy/regulatory system) and their histories and means of resilience (fiscal policy, governance mechanisms). In this respect, I suggest that discourses of Arctic development remain subtly inflected with the geopolitical past such that even simple cost-benefit analyses - "warming will damage pipeline/road infrastructure (cost) but increase the viability of ocean transport (benefit)" say - are underlain by the historical contradistinctions between Mackinder's (1904) 'Heartland Theory' and Mahan's (1890) 'The Influence of Sea Power upon History'. Having drawn out these political undercurrents, I conclude with Stephenson's (2013) paper on 'collaborative infrastructures' and the 'potentials for inter-state cooperation on the permafrost problem' which might cast off the geopolitical past and promote stronger economic development for the Arctic regions in the future.

Permafrost is defined on the basis of temperature as: ground (soil and/or rock) that remains at or below 0°C for at least two consecutive years. French (2009) extends upon this definition, stating that 'permafrost is not "permanently-frozen ground" as originally conceived by its coiner S.W Muller (1943) but "perennially-frozen ground" which expresses a broad latitudinal distribution governed by climate.' Interestingly Muller in the same paper would write presciently: 'the destructive action of permafrost phenomena has materially impeded the colonisation and development of extensive and potentially rich areas in the north. Roads, railways, bridges, houses and factories have suffered deformation, at times beyond repair, because the *condition* of permafrost ground was not examined beforehand, and because the *behaviour* of frozen ground was little, if at all, understood' [italics my own] (Muller, 1943)

There are further site-specific controls such as the thermal conductivity and diffusivity of earth materials, vegetation and snow cover, topography, aspect, fire and water bodies that produce zonal anomalies. Approximately 23-25% of the land surface area of the northern hemisphere is underlain by permafrost, with variations in thickness from a few centimetres (the young Mackenzie Delta, USA) to several hundred metres (Northern Yakutia, Siberia -1600m). As a generalisation, permafrost in Russia is thicker and colder than in North America and reflects the differences in Quaternary glacial histories between them. Gerasimov (1968) writes:

> 'during much of the Pleistocene, ice sheets covered the majority of Arctic North America but in Siberia ice sheets only formed in the principal mountain belts and uplands, leaving lowlands largely ice-free. An additional factor is that the retreat of Late-Pleistocene ice sheets in North America was accompanied by development of extensive postglacial lakes and marine inundations. These limited the land areas exposed to low sub-aerial air temperature, explaining the less-well developed Pleistocene periglacial zone in southern Canada and the northern United States' (Gerasimov, 1968).

Source:International Permafrost Association, 1998.
Circumpolar Active-Layer Permafrost System (CAPS), version 1.0.

Figure 1. Permafrost regions of the Northern Hemisphere (French, 2008). Note that the continuous zones are established at the highest polar latitudes, with discontinuous and sporadic permafrost occurring along a thermal-latitudinal gradient southwards thereafter.

By contrast, ice-free areas occurred widely in Siberia throughout the Pleistocene, conditioned by its continentality and topography (the Himalayas and Tibetan Plateau prevented the penetration of moisture-laden winds) to form deep and continuous permafrost in response to low air temperatures.' French (2008) further suggests that the lowlands of Central and Northern Siberia are 'exceptionally well-suited to thermokarst (thaw-weakened permafrost) development' due to the strong presence of ground ice (50-80% by volume). Re-tracing the geomorphological history of the region and its unglaciated profile during much of the Quaternary, he posits that the presence of these 'large syngenetic ice wedges - exceeding 50–60m in vertical extent in some areas - were produced because the lowlands 'acted as a stable aggradational region in which alluvial sediments were deposited under cold-climate conditions over a long period of time.'

Wadhams et. al (1991) further place these distributions of permafrost within a causal framework that accounts for processes occurring at different scales and temporalities: (i) global/continental climate patterns (ii) regional atmospheric/oceanic circulations (iii) local topographic causes (form/aspect, vegetation cover). Observing the embeddedness of the local within the global, they raise the problematic of distinguishing between microclimatic and broader, climatic amelioration effects on permafrost behaviour; for instance, Demek (1994), stressing the embeddedness of permafrost dynamics within a broader geomorphic (fluvial-glacial) system, would dystopically postulate a 'catastrophic scenario' in Eurasia in which widespread subsidence/thermokarst development in the Siberian floodplains allowed 'the transgression of cold Arctic ocean water into the lower reaches of Siberian rivers', impacting local fishing economies and flooding river settlements.

French (2008) suggests that, because it is difficult to generalise about the global distribution of thermokarst and locate it within a particular scalar framework, cryologists focus on drawing out several general observations. Firstly, thermokarst develops best in unconsolidated ice-rich sediments rather than in bedrock, reflecting the structural coherence of bedrock and the fact that fine-grained sediments promote ice segregation. Secondly, thermokarst is largely absent from many of the ice-free areas of the extreme polar latitudes due to their aridity and low ground-ice amounts in the near-surface sediments.

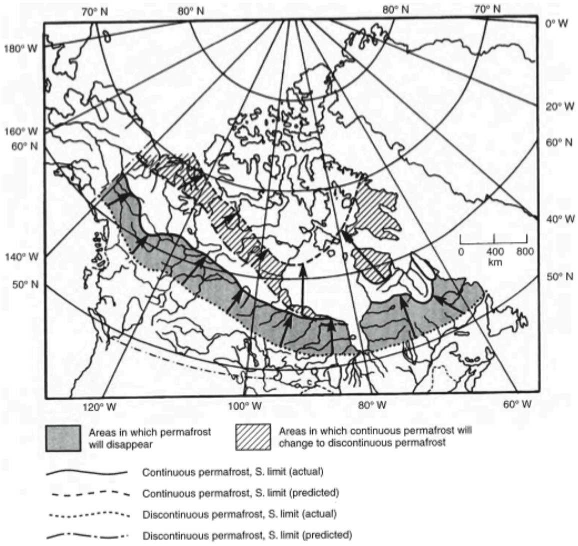
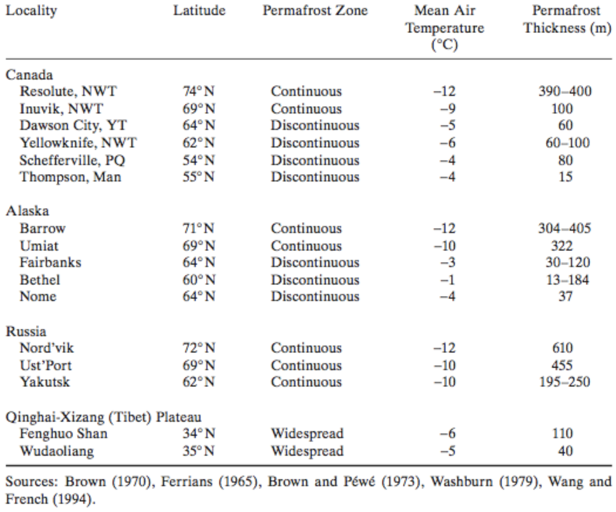


Figure 2. Predicted changes in permafrost extent in Canada as the result of a surface temperature increase of 4°C (Atmospheric Environment Service, 1990). *Note how in continuous permafrost, the active layer thickens and permafrost decreases in thickness from both top and bottom. In discontinuous permafrost however, the permafrost may actually disappear.*



Locality	Latitude	Permafrost Zone	Mean Air Temperature (°C)	Permafrost Thickness (m)
Canada				
Resolute, NWT	74° N	Continuous	–12	390–400
Inuvik, NWT	69° N	Continuous	–9	100
Dawson City, YT	64° N	Discontinuous	–5	60
Yellowknife, NWT	62° N	Discontinuous	–6	60–100
Schefferville, PQ	54° N	Discontinuous	–4	80
Thompson, Man	55° N	Discontinuous	–4	15
Alaska				
Barrow	71° N	Continuous	–12	304–405
Umiat	69° N	Continuous	–10	322
Fairbanks	64° N	Discontinuous	–3	30–120
Bethel	60° N	Discontinuous	–1	13–184
Nome	64° N	Discontinuous	–4	37
Russia				
Nord'vik	72° N	Continuous	–12	610
Ust'Port	69° N	Continuous	–10	455
Yakutsk	62° N	Continuous	–10	195–250
Qinghai-Xizang (Tibet) Plateau				
Fenghuo Shan	34° N	Widespread	–6	110
Wudaoliang	35° N	Widespread	–5	40

Sources: Brown (1970), Ferrians (1965), Brown and Péwé (1973), Washburn (1979), Wang and French (1994).

Figure 3. Permafrost depths and mean annual air temperatures at selected locations in the Northern Hemisphere (French 2008). *Note how the type and thickness of permafrost changes with increasing latitude such that generally: higher latitude, lower temp. = thick, continuous permafrost; and lower latitude, warmer temp. = thin, discontinuous permafrost. Further empirically shown is the generalisation that permafrost in Russia is thicker and colder than in North America.*

Permafrost, under Demek and other cryologists' understanding, is usually classified in its extent as being continuous (90–100%), discontinuous (50–90%), sporadic (10–50%), or isolated (0–10%). Much current Arctic discourse concerns the potential, socioeconomic loss in discontinuous and sporadic zones where the ground temperature straddles near the critical, thermal threshold of 0°C. Distinguishing permafrost typologies further the International Permafrost Association (2009) states that:

> in areas of continuous permafrost, frozen ground is present at all localities except for locally unfrozen zones, usually existing beneath lakes and river channels. In discontinuous permafrost terrain, bodies of frozen ground are separated by areas of unfrozen ground. Where permafrost is sporadic or isolated, it is usually restricted to isolated "islands," often occurring beneath peaty organic sediments.

French (2008) adds, 'in discontinuous and sporadic permafrost, the vegetation cover and organic mat are crucial to permafrost preservation and, if disturbed for any reason, thermokarst may be initiated [whereas] in terrain underlain by cold permafrost, thermokarst may be less important because the active layer is shallow, the period of summer thaw is short, and the thermal change required to initiate thermokarst is large.' Nearly one-half of Canada and 80% of Alaska are underlain by permafrost. In Russia, nearly 50% is underlain, most occurring in the forest zone east of the Yenesei River. As early as 1960, cryologists had mapped the continuous permafrost distribution of North America - from the Canadian Arctic Archipelago and Southern Alaska (500m depth) to its southern limit (15m) at the shores of the Hudson Bay - and observed that the latter generally coincided with the position of the −6°C to −8°C mean annual air temperature isotherm (Brown, 1960). In key, the southern limit of discontinuous permafrost - deeper south of the Hudson Bay - roughly coincided with the −1°C mean annual air temperature isotherm. Such discontinuous permafrost is also encountered in limited areas of northern Scandinavia, the Kola Peninsula, and the tundra and boreal forest areas

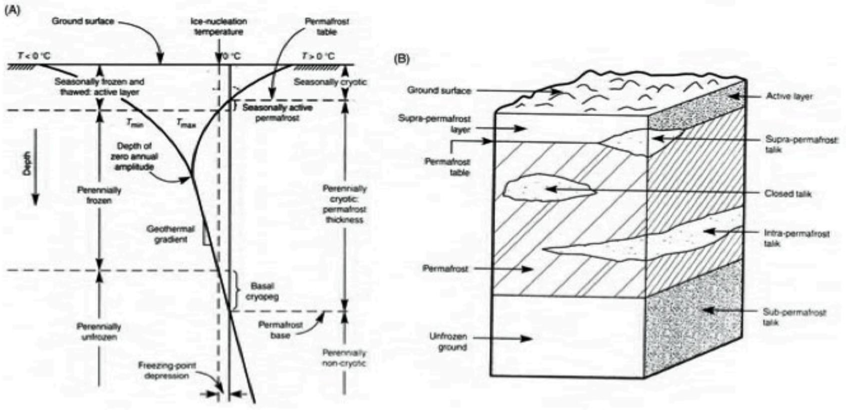


Figure 4. The behavioural dynamics of Permafrost (Ferrians et. al, 1969) The permafrost table is the upper surface of the permafrost and the ground above the permafrost table is called the supra-permafrost layer. The active layer - seasonally-frozen ground that freezes in winter and thaws during summer - is found within this supra-permafrost layer. *(A) Typical ground-thermal regime indicating maximum and minimum temperatures, the decrease in temperature with depth, the geothermal gradient, the depth of zero-annual amplitude, and the depth of seasonal thaw (the active layer). (B) The relationship between permafrost, the permafrost table, the active layer, and supra-, sub-, and intra-permafrost taliks (unfrozen zones).*

between the White Sea and the Ural Mountains. East of the Urals, notes French (2008), a broad zone of discontinuous permafrost exists across western and eastern Siberia. Here, 'the transition from discontinuous to continuous permafrost coincides approximately with the northern boundary of the boreal forest (taiga; 25-30m depth) and is accompanied by a sharp increase in thickness of permafrost (the tundra zone; 400m).

Understanding the properties and behavioural dynamics of frozen ground (Figure 4), particularly its linear and non-linear responses to warming, forms the foundation of geocryology and modern geo-engineering. Moisture processes associated with freezing and thawing condition the behaviour of underlying permafrost, particularly in the active layer. As I will explore later, understanding these processes forms a critical component of geo-engineering and the calculation of permafrost stability for construction purposes. Whiteman (2011) writes, 'the thickness affects the heave potential during the freeze-back in the cold season [with] a thicker active layer imparting greater heave stresses on surface structures and their supporting piles.' Furthermore, the geothermal regime of such permafrost reflects a negative heat balance at the surface of the earth, with the thickness determined by a balance between the internal heat gain with depth and heat loss from the surface. Observing the geothermal disturbance of thaw-lakes in the Sachs River lowlands of Canada, Smith (1973) would pioneer the examination of permafrost growth in terms of heat-conduction theory:

> Assuming an idealized homogeneous crust in thermal equilibrium, the distribution of ground temperature is a linear function of depth. Thus, the temperature regime in permafrost can be treated in a simple one-dimensional model:
>
> $$Qg=K(\mathrm{d}T\ \mathrm{d}z)$$
>
> where Qg is heat conduction into the ground, K is thermal conductivity, and $\mathrm{d}T/\mathrm{d}z$ is the thermal gradient. Obviously different earth materials have different thermal conductivities.

The thermal dynamics of permafrost are thus such that if there is any directional or intensity change in the climatic conditions at the ground surface (Figure 5) - in other words a disruption of the thermal equilibrium - then permafrost (active layer) thickness will respond accordingly. This change in thickness is further conditioned by microclimatic and topographical factors such as the gradient and aspect of the land, vegetation cover and type, and rock and soil properties. Ground-ice and the volumetric transitions between solid and liquid phases around the critical 0°C temperature threshold play a significant role in the development of thermokarst and processes of frost heave and thaw subsidence. Fundamentally, frost heave is dependent upon the extent of water present in the permafrost body, which is itself conditioned by the structural characteristics of the ground wherein 'the more fine-grained the soil is, the greater the amount of water remaining at a given negative temperature' (Slaymaker et. al, 2007). Frost heave, particularly associated with the Arctic winter and the fall in atmospheric-ground temperatures, then occurs as the water volumetrically expands by 9% during its phase change (freeze) to ice. French (2008) suggests that this expansion is exacerbated (positive feedback) by the behaviour of water restricted to unfrozen zones (taliks), such that 'as the water content is reduced by progressive formation of ice, the remaining water is drawn toward the freezing soil by osmosis and, on entering the frozen zone, becomes ice.' That the frozen soil then contains a greater amount of ice results in frost heave which can undermine structures within the permafrost by effectively "pushing" them vertically out of their dug-in position.

Processes of thaw subsidence are intimately entwined with frost heave and both can either precede or succeed one another to weaken the stability of the permafrost. Following on from the frost heave described above, thaw subsidence occurs as the ice held in a frozen state thaws and volumetrically contracts, leading to ground subsidence. Further thaw consolidation often occurs at this thawed sediment compacts and settles under its own weight. French (2008) links this process to the wider geomorphic system, positing how the 'high pore-water pressures generated [can] produce soil instability and mass movement, particularly on slope terrain [and] in unconsolidated and/or soft sediments of flat plains [where] there is often a significant loss of bearing strength upon thawing.' In the high latitude continuous zones where temperatures are lower and phase-change processes less frequent, there remain permafrost hazards. This is because even if ice just warms its shear strength decreases and it becomes more susceptible to creep or failure; Davies et. al's (2003) research on joint surfaces following rock falls in the Alps in the heatwave summer of 2003, revealed how failure often occurs at sub-zero temperatures due to the lubricating effects of thaw-released water bodies and the reduced bonding capacity or strength of rock-rock contact as opposed to ice-ice. As such, the engineering design of infrastructures built on permafrost must take into account multiple processes with differing temporalities and effective durations within the periglacial system; Whiteman (2011) writes, 'strong design accounts for the seasonal thaw (active layer) depths and permafrost temperatures expected during the lifetime of the structure, not just those applicable during construction, as these parameters control key cryogenic processes, such as creep, thaw settlement, adfreeze bonding and frost heaving.' Such design has to further account for the risks associated with other geomorphic elements or subsystem effects upon

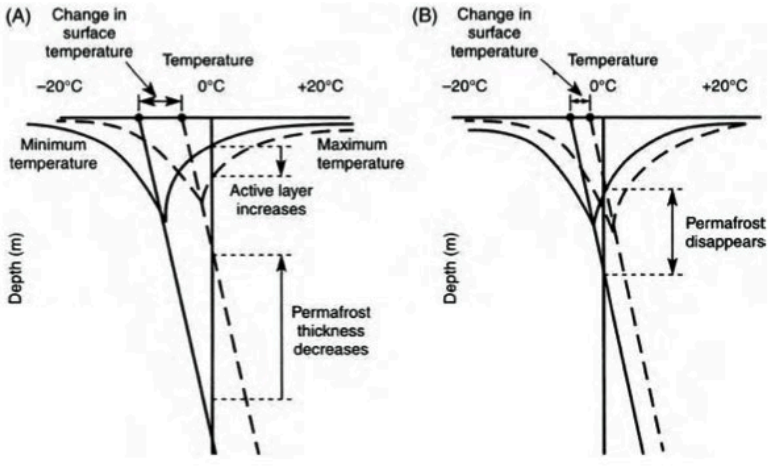


Figure 5. The long-term effect of a 4°C warming upon the ground temperature profile (Whiteman, 2011). *Note the differential responses of (A) the continuous permafrost zone and (B) the discontinuous permafrost zone. In both cases, the active layer thickens and near-surface permafrost thaws. In discontinuous permafrost however, where ground temperatures are close to 0 °C, thaw degradation results in disappearance of permafrost. In situation (A), permafrost degrades in the near-surface and decreases in overall thickness.*

permafrost stability (Figure 6), of which they, the engineers themselves are deeply implicated. French (2008) reiterates the significance of the fluvial system, wherein:

> thermokarst [can be] associated with stream incision acting preferentially along ice wedges causing the undermining and slumping of overlying material, tunneling and piping. [Further] lateral stream erosion can initiate thermokarst activity [exemplified by] the retrogressive slaw slumps that occur mainly upon steeper west- and south-west facing slopes of asymmetrical valleys on eastern Banks Island (French, 2008).

Further local triggers for thermokarst include ice-push and scour along coasts, cyclical changes in vegetation, lightning-induced forest fires, slope instability and deforestation or disruption of the surface by human activity. Superimposed upon the broader realised *and* simulated changes of climate change (warming was observed in sub-Arctic Siberian permafrost ranging from 0.6-0.7°C between 1970-1990 (Pavlov, 1994); warming is predicted to produce mean annual winter temperatures 5°-10°C warmer than present levels by 2100 (Slaymaker et. al, 2007)) these trigger actors play a significant part in thermokarst development (subsidence, erosion, runoff and slope instability) and the subsequent disruption and damage of human infrastructures.

Fundamentally, in examining the disruption of human structures by permafrost degradation, I delineate broadly between public/sedentary (municipal services, housing) and private/mobile (mining-industrial complex, oil-gas transport) element of the human infrastructure. The provision of municipal services and urban infrastructure such as water supply and sewage disposal is particularly challenging in permafrost regions because 'systems will often freeze if left unprotected above ground yet it is costly and difficult to excavate trenches either to depths below the seasonal-frost level or within permafrost' (Instanes et. al, 2007) Therefore, pipes to carry municipal services cannot be laid below ground, as is normally the case in non-permafrost regions, because heat from the pipes will promote thaw of enclosing permafrost and subsequent subsidence and fracture of the pipe. Problems associated with buildings and roads further relate to frost heaving and thaw subsidence in which successive cycles of heave can progressively lift piles, in the same manner that frost-jacking of bedrock occurs. French (2007) posits that the 'annual cost of rectifying seasonal-frost damage in roads, utility foundations and buildings in areas of permafrost and deep seasonal-frost, as present in areas of Canada, Alaska, Sweden and northern Japan, is considerable [..] with the costs of upgrading some of the ageing and more primitive infrastructures of norther Russia even greater.' Water-supply problems are further caused because permafrost acts as an impermeable layer and thus restricts the movement of groundwater to thawed zones or taliks. In addition, supra-permafrost water is often subject to near-surface contamination and intra-permafrost water to extensive mineralisation and difficulty to locate, thus raising the critical importance of tapping sub-permafrost water to Arctic communities.

Disruption of public, sedentary infrastructures of the Arctic engage a demographic of between five and eight million people - spread throughout Alaska, northern Canada, Greenland, Scandinavia and Russia - deep within the permafrost/economic development discourse. Furthermore, increasingly so these populations are congregating within a number of cities with populations in excess of 20,000-50,000 persons. As French writes, 'in Russia, there are nearly a dozen mining cities, such as Norilsk or Vorkuta, with populations in excess of 50,000-100,000 persons all situated in areas of warm or discontinuous permafrost' and in North America there are the administrative centres such as Fairbanks,

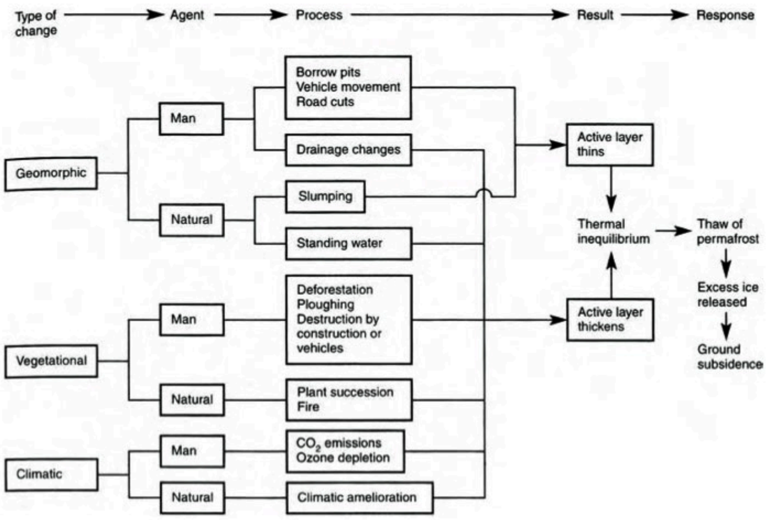


Figure 6. Thermokarst development and its geomorphic, vegetational and climatic causes (Whiteman, 2011) *Note that many of the processes occur either in tandem or succession to one another and their risks can be predicted or mitigated to some effect. For instance, risk-mapping research performed by Instanes et. al (2004) opens: 'Destructive impacts of thawing permafrost on human infrastructure are not necessarily abrupt; in many cases they evolve gradually and may be predicted probabilistically using permafrost scenarios. In our study we used a methodology based on the geocryological hazard index,* I_G*, which is the combination of the projected change in active-layer thickness, expressed in relative units with respect to modern norm, and the volumetric ground ice content'*

Iqualhuit and Yellowknife. Observing the infrastructural disruption of thermokarst in Yellowknife, NWT over several decades, Wolfe (1998) historicises the permafrost/economic development discourse. Yellowknife is the largest community in the NWT rapidly growing demographically that owes its original existence to mining of gold and other minerals but is now also the administrative centre of the NWT and a logistics base for diamond mining and other operations. Wolfe (1998) focuses on one particular building construction and its subsequent disruption, he writes:

> The Rockcliffe apartment building is a three storey residential building, initially constructed in 1974 on piles drilled through surficial materials to underlying bedrock. A heated crawl space that was present beneath the building [however] resulted in thaw settlement of underlying sediment. The crawl space enlarged from 1m to 4m in height over a 20-year period (Figure 7). The piles became stressed and the building began to shift. In 1994 the expanded crawl space was filled and levelled with aggregate and thermosyphon tubes were installed to remove heat from within the fill. By 1997, the infill had cooled to 0C and quasi-stability of the piles had been re-established (Wolfe, 1998).

In similar vein, Khrustalev's (2000) research on the major geo-engineering and geotechnical problems of northern Russia's cities disclosed that 'frost-jacking, thaw subsidence around buildings, deterioration of water and sewage facilities, and a general lack of maintenance due to fiscal concerns and poor management were widespread.' The same study concluded with the stark prediction that '50-60% of all major buildings constructed between 1950 and 1999 will have failed.' That these processes of the sedentary, political economy initiate thermokarst development has become increasingly recognised by state and energy-industrial capitalist actors, who themselves face major problems associated with resource exploration and the construction of pipeline and transport infrastructure. As French (2008) discloses, 'the periglacial environment contains appreciable quantities of natural resources and in the past 30 years, the major stimulus for much economic development in Arctic North America and in northern Russia has been the exploitation and development of energy reserves, notably hydrocarbons.' As Yellowknife's migratory history (above) suggests, the development of this private, exploratory-mobile infrastructure to extract such hydrocarbons is deeply entwined with public/sedentary infrastructure. There are further unusual interlinkings to be made. Along with the inherent tendency of the capitalist political economy and its state-industrial actors to seek surplus and 'accumulate by dispossession' (Harvey, 1999) has come the economic realisation that human welfare and prosperity is deeply entwined with the welfare of non-human elements of the land. Instanes's (2002) research on Siberia and the post-Soviet community of Norilsk frames the "permafrost problem" within an Actor Network Theory perspective, he writes:

> [with the] structures on permafrost it is often difficult to differentiate between the effect of temperature increases [non-human] and other factors [human error] that may affect a structure on permafrost. For example: the site conditions are different from the assumed design site conditions; the design of the structure did not take into account appropriate load conditions, active-layer thickness, and permafrost temperature; the contractor did not carry out construction according to the design; the maintenance program was not carried out according to plan; and/or the structure is not being used according to design assumptions.

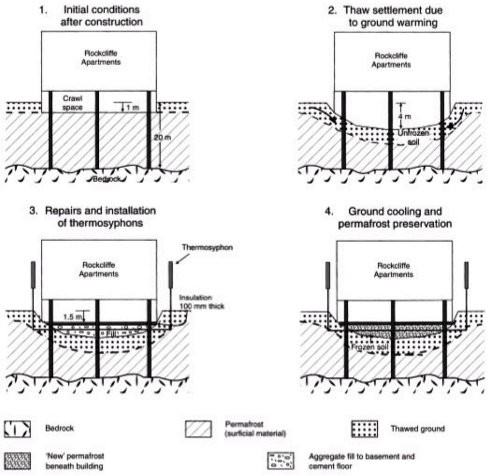


Figure 7. Infrastructural disruption due to thermokarst - thaw subsidence and the weakening of pile foundations in Yellowknife, Canada (Wolfe, 1998)

Processes of the political economy such as construction and land clearance may initiate thermokarst development has become increasingly recognised by state and energy-industrial capitalist actors. As French (2008) discloses, 'the periglacial environment contains appreciable quantities of natural resources and in the past 30 years, the major stimulus for much economic development in Arctic North America and in northern Russia has been the exploitation and development of energy reserves, notably hydrocarbons.' Along with this inherent tendency of the capitalist political economy to seek surplus and 'accumulate by dispossession' (Harvey, 1999) however, has come the economic realisation that human welfare and prosperity is deeply entwined with the welfare of non-human elements of the land. Instanes's (2002) research on Siberia and the post-Soviet community of Norilsk frames the "permafrost problem" within an Actor Network Theory perspective, he writes:

> [with the] structures on permafrost it is often difficult to differentiate between the effect of temperature increases [non-human] and other factors that may affect a structure on permafrost. For example: the site conditions are different from the assumed design site conditions; the design of the structure did not take into account appropriate load conditions, active-layer thickness, and permafrost temperature; the contractor did not carry out construction according to the design; the maintenance program was not carried out according to plan; and/or the structure is not being used according to design assumptions.

Disruption of private, mobile infrastructures has been extensively recorded throughout Alaska and northern Canada where several railways have experienced costly maintenance problems on account of frost heave adjacent to bridge structures and thaw settlement along the railbed itself (Ferrians et al., 1969). The Hudson Bay railway, which extends through northern Manitoba to the port of Churchill is one such case. During nearly 60 years of operation, thaw settlement of the railway embankment and destruction of bridge decks by frost heave have been perpetual problems. Hayley (1988) posits how 'test sections installed with heat pipes proved effective but costly measures that minimised thaw subsidence.' However the numerous transitions from frozen to unfrozen terrain in discontinuous permafrost terrain made installation of such techniques along the entire 820km route impractical. Oil and gas development in the Arctic region have further been stalled and disrupted by permafrost degradation. Seligman (2000), mindful to trace an authentic chronology and reiterating Instanes (above), suggests that disruption was itself often initiated or triggered by the poor environmental and regulatory practices of the industry. Lawson (1978) furthermore stresses that this was not necessarily conscious negligence, he writes of the early exploration of Alaska in the 1940s, and the subsequent development of the Prudhoe Bay oilfield by the US Navy Petroleum Reserve: 'at the time, there was little understanding of the sensitivity of tundra terrain to disturbance. Drilling was undertaken in both summer and winter months, vehicles were moved randomly across the tundra, and waste-drilling was discarded at the site.'

Such practice continued at the site well into the mid-1970s when environmental and regulatory measures were enacted by the Federal Government, such as the Territorial Arctic Land Use Act and Regulations, to minimise this sort of environmental damage. The regulations largely restricted vehicle movement and drilling activity to the winter months, and imposed numerous other drilling procedures and management practices related to safety and environmental concerns (as I will argue in the next paragraph, the imposition of this regulatory structure locates more broadly into a positive "coevolutional" perspective on human and non-human infrastructures in the Arctic). Seligman (2000) traces a similar history of exploration in the northern Russia and posits, that 'in spite of modern environmental practice, terrain and environmental damage continue to occur in the Yamal and Gydan regions of western Siberia, where regulatory procedures are frequently avoided or minimised.' Superimposed upon these localised interactions of permafrost and industry are the broader effects of natural dynamics of climate variability (annual) and amelioration (decadal; natural as well as human-induced) which complicate the construction of pipelines and other extractive infrastructures in the Arctic region. French (2008) locates the complexity of constructing the Trans-Alaska Pipeline System (TAPS) from Prudhoe Bay on the North Slope to Valdez on the Pacific coast during the 1970s to the problems of discontinuous permafrost related to frost heave and thaw weakening, he writes:

> Inevitably, oil is "warm" and the ease of transmission through a pipeline varies with viscosity. [TAPS] utilised many procedures designed to minimise permafrost problems. Approximately half the route was elevated on vertical support members (VSMs), many with cooling devices ("heat tubes") to prevent heat transfer from the warm pipe to ice-rich (i.e. thaw sensitive) permafrost...However, for security reasons, the pipeline had to be buried in certain places leading to the prolonged frost heave rupture adjacent to the pipe and, where the pipe passed from unfrozen (stable) to ice-rich (unstable) terrain disruption of thaw settlement along its bottom' (French, 2008).

Nixon (1990) draws the Trans-Alaska Pipeline System and similar capitalist infrastructure into a global political economy perspective suggest that regulatory issues, market demand and world energy supply will largely determine the construction of new pipelines for oil and gas in both North America and siberia. He adds, 'what is clear is that a thorough and in-depth understanding of the permafrost-terrain-vegetation relationship is required for modern resource development in northern regions [with] most enlightened companies and regulatory agencies today maintaining "environmental personnel and departments...progressive planners, developers, real estate agencies, and mortgage lenders incorporat[ing] permafrost into their decision-making processes.'

Mann (2009) locates the increasing state-private actor interest in the Arctic to a broader geopolitical shift in which local communities, through increased connectivity to, and cultural exchange, with metropolitan centres become less politically isolated. Delineating between "infrastructural" (local; embedded) and "despotic" (distant, disembedded) modes of power (Figure 9), he traces future opportunities in a warming climate for the state actors to positively integrate local, Arctic economies into the petro-capitalist system. Makarov (2010) further suggests that beyond the state

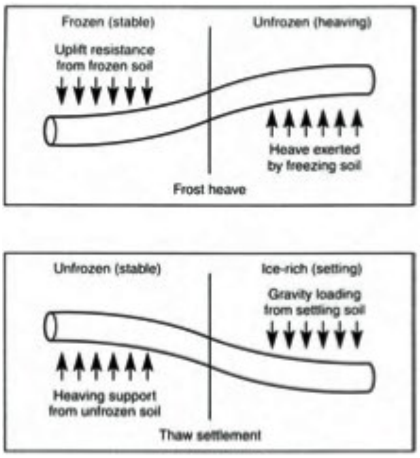
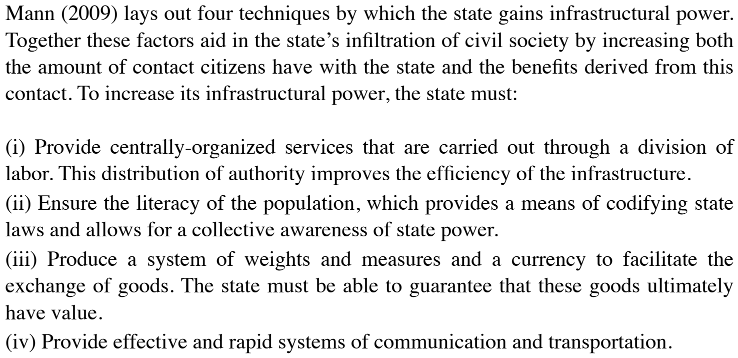


Figure 8. The freezing and thawing effects of a buried, chilled gas pipeline crossing from unfrozen to frozen terrain, and vice versa, in an area where permafrost was discontinuous (Nixon, 1990 cited in French, 2008)



Mann (2009) lays out four techniques by which the state gains infrastructural power. Together these factors aid in the state's infiltration of civil society by increasing both the amount of contact citizens have with the state and the benefits derived from this contact. To increase its infrastructural power, the state must:

(i) Provide centrally-organized services that are carried out through a division of labor. This distribution of authority improves the efficiency of the infrastructure.
(ii) Ensure the literacy of the population, which provides a means of codifying state laws and allows for a collective awareness of state power.
(iii) Produce a system of weights and measures and a currency to facilitate the exchange of goods. The state must be able to guarantee that these goods ultimately have value.
(iv) Provide effective and rapid systems of communication and transportation.

Figure 9. Local economic development in the Arctic as infrastructural integration into the capitalist economy. Taken from Mann (2009) in Stephenson's paper on Arctic 'Collaborative Infrastructures' (2013).

and private profit-orient interests, civil society actors are deeply engaged in the Arctic permafrost dilemma, particularly climate change activist networks who recognise that 'because of the positive feedbacks associated with the release of greenhouse gases as permafrost degrades, and because of the albedo effects associated with reduced snow and sea-ice covers, a degrading Arctic will be a major contributor to enhanced global warming.' Such activism illuminates why Arctic development remains on such politically, economically and ethically contentious ground within policy circles , particularly in an Arctic Council that promotes participatory environmental governance and open, democratic dispute at every stage of the the decision-making process.

To observe broad and positive development futures in the Arctic, Mann (2009) recognises the growingly diffuse literature upon human infrastructures that (co)operate constructively with non-human ones to mitigate the risks of permafrost degradation upon Arctic communities. The progress of 'geoengineering' in this sense underlies the broad improvements made in industrial and constructional practices by Arctic state and private actors. Modern construction techniques aim to maintain the thermal equilibrium of the permafrost and avoid the onset of thermokarst through a range of novel solutions. The most common technique is the use of a pad which is placed on the ground surface to compensate for the increase in thaw which results from the warmth of the structure. French (2008) suggests that judging the required thickness of the pad forms a critical and difficult part of infrastructural development in the Arctic: too little fill, plus the increased conductivity of the compacted active layer beneath the fill, and the result is thawing and subsidence; too much fill (over-insulation) and the permafrost surface will aggrade on account of the reduced amplitude of the seasonal temperature fluctuation. Further sophisticated techniques are utilised still, often where 'large quantities of high quality non-frost susceptible aggregate are scarce and the structure justifies the cost' (French, 2008). Instanes (2004) explores how the Yukon government constructed two 350m^2 multi-purpose municipal buildings in the communities of Ross River and Old Crow, using heat-pump chilled foundations. The aim, he writes, was to prevent the thaw of permafrost beneath the building and improve energy efficiency with one stone:

> At Ross River, located in the discontinuous permafrost zone, the permafrost is marginal and the mean annual ground temperature between 0°C and - 0.5°C. To prevent thaw, heat exchangers were placed in a sand layer within the granular fill used to level the site. Heat flowing down through the floor is then

> captured by the heat exchangers and pumped back into the building. [Thus] while the building is being heated the ground is being chilled (Instanes, 2004).

Instanes's research thus re-engages with Latour's (1994) 'actor network theory', mobilising its political legitimacy within wider, Arctic development discourse(s) by re-instating, largely unintentionally, the deeply intertwined and embedded relationship between human (infrastructure/political economy) and non-human ('frozen ground'/natural resources) structures in the Arctic.