Permafrost in Svalbard: An Audit of Examination History, Climatic Foundation and Designing Difficulties

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Abstract: This paper audits permafrost in High Arctic Svalbard, including past and ebb and flow research, climatic foundation, how permafrost is impacted by climatic change, common permafrost landforms and what changes in Svalbard permafrost might mean for regular and human frameworks. Informa-tion on dynamic layer elements, permafrost and ground ice qualities and chose periglacial highlights is summed up from the new writing and from unpublished information by the writers. Permafrost thickness goes from under 100 m close to the coasts to in excess of 500 m in the good countries. Ground ice is available as rock icy masses, as ice-cored moraines, burie 191/39d frigid ice, and in pingos and ice wedges in significant valleys. Designing issues of defrost settlement and ice hurl are portrayed, and the implications for street plan and development in Svalbard permafrost regions are examined.
Keywords: High Arctic Svalbard, Dynamic layer elements, Defrost settlement

1. Introduction

Recent changes in the Arctic atmosphere–ice– ocean system have sparked intense discussions as to whether these changes represent episodic events or long-term shifts in the Arctic environment. Concerns about future climate change stem from the increasing concentration of greenhouse gases in the atmosphere. During the last 15 years the Arctic has gained a prominent role in the scientific debate regarding global climatic change (Houghton et al. 2001). Existing knowledge on Quaternary climate and Global Climate Models predicts that the effect of any present and future global climatic change would be amplified in the polar regions due to feedbacks in which variations in the extent of glaciers, snow, sea ice, permafrost and atmospheric greenhouse gases play key roles. Recent subcontinental-scale analysis of meteorological data obtained during the observation- al period lends empirical support to the alleged high climatic sensitivity of the Arctic (Giorgi 2002). Recently, however, Polyakov, Akasofu et al. (2002) and Polyakov, Alekseev et al. (2002) presented updated observational trends and variations of Arctic climate and sea ice cover during the 20th century which do not support the modelled polar amplification of temperature changes observed by surface stations at lower latitudes.

There is reason, therefore, to evaluate cli- mate dynamics and their respective impacts on high latitude ecosystems, including permafrost regions. The latter currently occupies 20 - 25 % of the land surface of the Northern Hemisphere (Péwé 1983; Zhang et al. 2000). Slight changes in mean annual air temperature, wind speed and precipitation have the potential to change the state of large regions of currently frozen ground (Nelson et al. 2001, 2002; Anisimov et al. 2002).

This section outlines research on permafrost in Svalbard, an archipelago of 63 000 km^2, since the late 19th century. This example of an early international research effort was, especially during the first years, dominated by Nordic researchers. Some of the publications referred to below are published in Norwegian or other Nordic languages only. As such, they are not always easily accessible to an international audience. The research focus has traditionally been on the main island, Spitsbergen. Among many fi ne scientists, one in particular stands out: Olav Liestøl (1916–2002), who provided ideas and inspiration for many Nordic permafrost scientists active in Svalbard.

Permafrost was known to be present in Svalbard at least since the First International Polar Year in 1882 and the fi rst coal mining operations in 1898. Ekholm (1890) measured ground temperatures at different depths below the terrainsurface at Kapp Thordsen in 1883. He was able to demonstrate temperature variations to a depth of 2 m. Later, Holmsen (1913) studied ground ice in Colesdalen, central Spitsbergen. Observing ground ice at several sites below the upper marine limit, he was probably the first to demonstrate a late Holocene age for permafrost and ground ice at low altitudes in Svalbard.

Werenskiold (1922) published the first review of frozen ground phenomena in Spitsbergen. Other early observations relating to Svalbard permafrost were carried out by Huxley & Odell (1924), Gripp (1926), Elton (1922, 1927) and Kulling (1937). From measurements of firn temperatures in the accumulation area of Fjortende Julibreen, Sverdrup (1935) was presumably one of the first to demonstrate that bedrock below large glaciers in Svalbard does not necessary need to be frozen. Orvin (1941) published descriptions of horizontal layers of ground ice (presumably refrozen ground water) from Spitsbergen. Later, Orvin (1944) addressed the apparent paradox of explaining permennial frozen ground.

Liestøl (1962) described so-called "talus terraces" from various sites in Svalbard. These rock-glacier-like features were described as consisting of recurrent layers of ground ice and debris, exposed to permafrost creep. Jahn (1960, 1965, 1967) described slope evolution, patterned ground, solifluction, rock falls and avalanches, including the June 1953 avalanche disaster in Longyearbyen. Jahn (1976) and Larsson (1982) both described another catastrophic mass movement event that affected Longyearbyen during a heavy rainstorm in August 1972. This event was due to saturation of unconsolidated near-surface sediments (the active layer) by heavy rain.

Liestøl (1976) was the first systematically to consider the thickness and thermal conditions of Svalbard permafrost. This classic paper describes the distribution of pingos, springs and permafrost in Spitsbergen. From observations made during mining operations, he was able to estimate the magnitude of the geothermal gradient—about 2 - 2.5 °C/100 m in central Spitsbergen. Péwé (1979) and Péwé et al. (1981) also discussed Svalbard permafrost in relation to climate and ongoing mining operations.

Several other papers merit identification in this review. For example, Liestøl (1976, 1980, 1986) measured permafrost temperatures and permafrost thickness in several deep boreholes on Spitsbergen, while Gregersen & Eidsmoen (1988) studied near-shore permafrost conditions at Longyearbyen and Svea. Salvigsen & Elgers- ma (1985)

and Salvigsen et al. (1983) discussed the issue of taliks and karst features in perma- frost in relation to large glaciers, major lakes or warm groundwater springs. Lauritzen & Bottrell (1994) described microbiological activity in some of these Svalbard springs. Finally, Landvik et al. (1988) discussed the possible occurrence of sub- marine permafrost on the shelf around Svalbard from a glacial-isostatic point of view.

The Norwegian Committee on Permafrost established the first site for Arctic engineering research purposes in June 1978, at Svea (Bakke- høi 1982; Bakkehøi & Bandis 1987, 1988). There, ground temperatures down to 8 m below a tundra surface and ground temperatures down to 2 m below an artificial concrete surface have since been collected. Further engineering aspects of permafrost in Svalbard are discussed by Gregersen (1988), Instanes (1988) and Orheim (1988). Sub- and intra-permafrost hydrological aspects have also been addressed by several workers, especially in relation to water supply at the Large-scale Research Facility in Ny-Ålesund, north-west Spitsbergen (e.g. Lauritzen 1991; Sandsbråten 1995; Haldorsen et al. 1996; Booij et al. 1998; Haldorsen & Heim 1999).

The vertical temperature profile of thick permafrost has recently been recognized as an important means of obtaining information on past surface temperatures. This is the object of a joint European research initiative, Permafrost and Climate in Europe (PACE), that has estab- lished a number of permafrost monitoring sites in a north–south European transect (Sollid et al. 2000; Isaksen et al. 2001; Isaksen, Humlum & Sollid 2003). The northernmost site is located on Janssonhaugen, in upper Adventdalen, central Spitsbergen. The temperature profile from the more than 100 m deep borehole clearly demon- strates the effect of a marked 20th century warming around 1920 as well as later meteorological variations (Isaksen, Ødegård et al. 2000; Isaksen, Vonder Mühll et al. 2000; Isaksen 2001; Isaksen, Humlum, Sollid et al. 2003).

Pingos are well-known phenomena in Svalbard. Svensson (1971) gave the first detailed description, based upon observations made in Adventdalen, near Longyearbyen. It was possible to obtain a maximum age for pingo initiation of about 2650 yr BP, suggesting a late Holocene age for permafrost near sea level in the region. The distribution and formation of pingos in Svalbard was further described and discussed in a seminal paper by Liestøl (1976). Yoshikawa & Harada (1995) present additional observations on the rate and timing of pingo growth in central Spitsbergen. Salvigsen (1977) and Åkerman (1982, 1987) discuss the sporadic occurrence of palsas in Sval- bard.

Ice wedges represent another typical example of geomorphic permafrost phenomenon present in Svalbard

(Svensson 1976). They have been the object of intermittent research, often in association with other activities. Detailed studies on ice wedge dynamics have been carried out in Adventdalen by Matsuoka (1999), who monitored thermal cracking, and by Jeppesen (2001), who excavated a number of ice wedges to study their structure and to obtain material for 14C dating and for oxygen isotope analyses. Recently, Christiansen (2003) has initiated a detailed monitoring scheme on air and ground temperatures, and automatic photographic registration of active ice wedges. Dating of organic material found in ice wedges (Jeppesen 2001) indicates that ice wedges near sea level have been initiated before about 2900 yr BP; this lends support to the dating of adjacent pingo initiation by Svensson (1971). Presumably, therefore, permafrost near sea level in central Spitsbergen is a late Holocene phenomenon in Svalbard (Humlum 2003).

Rock weathering is usually thought to be enhanced in permafrost areas when compared to non-permafrost areas, and a variety of publications on Svalbard talus morphology, avalanches, rock glaciers, debris flows, paraglacial slope processes and other processes and landforms have appeared (e.g. Rapp 1960; Liestøl 1962; Åkerman 1980, 1984; Sollid & Sørbel 1988a, 1992;

André 1990, 1994, 1997; Berthling et al. 1998; Berthling et al. 2000; Isaksen, Ødergård et al. 2000; Isaksen, Vonder Mühll et al. 2000; Isaksen 2001; Korsgaard 2002; Mercier 2002). Ødegård

& Sollid (1993) and Ødegård et al. (1995) have investigated near-surface spring temperatures in a coastal rock cliff near Ny-Ålesund and the possible implications for bedrock weathering in this special permafrost environment. Detailed investigations on meteorological parameters and bed- rock weathering rates have been carried out since 2001 in the near surroundings of Longyearbyen, by Prick (2003, in press).

Rock glaciers have been a research topic of great interest. Liestøl (1962) gave the first description of what are now known as rock glaciers, linking their formation to slope processes. The 1970s, 1980s and early 1990s saw several other investigations on the morphology of Svalbard rock gla- ciers (Chandler 1973; Swett et al. 1980; Humlum 1981; Lindner & Marks 1985; Dzierzek & Nitychoruk 1987), as well as their geophysical characteristics (Hoelzle 1993; Vonder Mühll 1996; Wagner 1996; Isaksen, Ødegård et al. 2000; Kääb et al. 2002; Ødegård et al. 2003a, 2003b).

The glacier–permafrost relation and its consequences for glacial sedimentology, hydrology and geomorphic activity have been investigated by Hambrey (1984), Liestøl (1986), Sollid & Sørbel (1988b), Ødegård et al. (1992);

Van der Water- en (1992), Lehmann (1993), Sollid et al. (1994), Vatne et al. (1995), Etzelmüller et al. (1996) and Boulton et al. (1999), while the relation between permafrost, supraglacial debris cover and the for- mation of debris-covered glaciers has been stud- ied by Korsgaard (2002). The coupling between climate change, permafrost and glacial sedimentology and dynamics has been the object of separate investigations (e.g. Hamilton & Dowd- eswell 1996; Glasser & Hambrey 2001). Murray et al. (2000) working at Bakaninbreen, south- ern Svalbard, especially stress the importance of permafrost for understanding surge-type glacier dynamics. Etzelmüller (2000) and Etzelmüller et al. (2000) studied surface changes in recently deglaciated permafrost terrain in four areas of Svalbard by comparing digital elevation models derived from aerial photographs. His study shows that thermo-erosion in deglaciated terrain is an important process, and that the average annual material mobilization due to thermo-erosion can be of the same order of magnitude as field-meas- ured total annual suspended sediment transfer out of the catchments. Large ice-cored moraines are found in association with many glaciers in Svalbard today; these may also be considered a permafrost-related landform. Melting of their ice cores by river erosion or climate change results in slope instability and variations in the sediment transport of rivers draining these areas (O. Liestøl, pers. comm. 1988).

Holmsen (1913) and Orvin (1941) provided some of the first observations on active layer thickness from Svalbard. Systematic monitoring of the active layer has been carried out in the vicinity of Kapp Linné since 1972 (Christiansen et al. 2003) and at Calypsostranda (south-central Spitsbergen) since 1986 (Repelewska-Pekalowa 1988; Christiansen et al. 2003). The active layer monitoring at Kapp Linné is the longest record in the world. Active layer monitoring has also been carried out at Janssonhaugen since 1998, at Longyearbyen since 2000 and at Ny-Ålesund since 2001 (Brown et al. 2000; Christiansen et al. 2003; Isaksen, Humlum, Sollid et al. 2003). Meteorological and other local controls on active layer depths in Spitsbergen have recently been the focus of detailed research (Putkonen 1998; Oht 2002, 2003). Roth & Boike (2001) investi- gated the dynamics of active layer temperatures from a mineral hummock field at Bayelva, on the Brøggerhalvøya peninsula, with special reference to conductive heat flux, generation of heat from phase transitions, and migration of water vapour. Active layer groundwater sampling has demon- strated that the principal means of solute acquisition for such water is the weathering of highly reactive active layer sediments by supra-permafrost groundwater (Cooper et al. 2002).

Recently, an interesting illustration of active layer thickness variations in Svalbard became apparent. The "Spanish Flu" killed over 40 mil- lion people worldwide in 1918. Seven men died of the disease in Longyearbyen that year and were interred in the local graveyard. Ground Penetrating Radar (GPR) was used to locate the seven coffins near the existing seven grave markers (Davis et al. 2000). The GPR indicated that the ground was disturbed to 2 m depth and was perennially frozen below 1 m. Subsequent excavation showed that the tops of the coffins were buried less than 1 m deep, and that the modern active layer where the coffins were located was 1.2 m deep. Thus, the victims were only partly in permafrost, but virological and bacteriological investigations on recovered tissues were possible and provided an opportunity to isolate and identify the microorganisms involved in the 1918 influenza.

2. Svalbard Climate and Permafrost

Weather in the Arctic is characterized by "semi- permanent" patterns of high and low pressure (Serreze et al. 1993; Serreze et al. 1995; Serreze & Barry 1998). These patterns are semipermanent because they appear in charts of long-term average surface pressure. They can be considered largely to represent the statistical signature where transitory high and low pressure systems that appear on synoptic charts tend to be most common. This pattern is relatively weakly developed in summer, but stronger in winter.

A major control, especially for winter weather and permafrost in the Svalbard region, is the Siberian High, an intense, cold anticyclone that forms over eastern Siberia in winter. Prevailing from late November to early March, it is associated with frequent cold air outbreaks over East Asia, and strong cooling in this region results in the lowest air temperatures in the Northern Hemisphere. During very cold winters the Siberian High extends to the west, covering Russia and parts of Europe. Airflow over the Nordic seas then is strong and southerly, causing advection of warm air to the Svalbard region, heavy snowfalls and quite often also periods of snowmelt even in the middle of winter. Conversely, when cold polar air masses extend over Svalbard, northern Europe is usually exposed to strong westerly airflow and heavy precipitation. Therefore, a thermal "sea- saw" between northern Europe and Svalbard is often registered during winter.

In winter periods with calm conditions, the weather in the Svalbard valleys is dominated by shallow inversions where warm air overlies colder air near the terrain surface, decoupling surface winds from stronger upper layer winds. For this reason, surface wind speeds tend to be lower in winter than one might expect and cold (and dense) air tends to accumulate in topographic lows. In summer and autumn, inversions are less frequent and weaker, and the movement of low pressure systems (cyclones) across Svalbard dominate the weather.

Special climatic interest is often attached to the Svalbard region because this part of the Arctic apparently displays a unique climatic sensitivity. This was recognized early by both Ahlmann (1953) and Lamb (1977). Significant climatic variations in the Svalbard region during the 20th century have been well documented by meteorological data since 1911 (Førland et al. 1997). For example, a marked warming around 1920 within 5 years changed the mean annual air temperature at sea level from about –9 °C to –4 °C. This is possibly the most pronounced increase in surface air temperature documented anywhere on the planet during the observational period. Later, from 1957 to 1968, the air temperature sharply dropped by about 5 °C, with a subsequent more gradual increase towards the end of the 20th century. In the latest Intergovnernmental Panel on Climate Change report (Houghton et al. 2001), attention is specifically drawn to the extraordinary high climatic sensitivity of Svalbard. This probably derives from three mechanisms. First, the islands are located directly in the main trans- port pathway for air masses into the Arctic Basin (Dickson et al. 2000). Second, Svalbard is located near the confluence of air masses and ocean cur- rents with very different temperature characteristics, and large-scale meteorological phenomena such as the Siberian High may especially influence winter temperature conditions. Finally, the sensitivity is further enhanced by rapid variations in the sea ice extent, coupled with both atmospheric and oceanic circulation (Humlum 2002; Shapiro et al. 2003).

At the beginning of the 21st century, the mean annual air temperature (MAAT) is about –5 °C close to sea level in central Spitsbergen, while the mean annual precipitation is around 180 mm w.e. The –10 °C MAAT isotherm is presently located at about 700 m a.s.l., according to unpublished meteorological measurements since 2000 by O. Humlum. Modern meteorological values are within the range of variability defined by the total Svalbard meteorological record; the warm- est period in the 20th century was around 1930– 1940. The average vertical precipitation gradient on Spitsbergen is 15 - 20 % (per 100 m) in the coastal regions, while it is somewhat small- er (5 - 10 %) in the central part of Spitsbergen (Hagen & Liestøl 1990; Hagen & Lefauconnier 1995; Killingtveit et al. 1996). The coastal– inland contrast in vertical precipitation gradient is assumed to be caused by enhanced orographic effects in the coastal regions compared to inland areas (Humlum

2002). As outlined below, this distribution of precipitation represents a control on permafrost development in Svalbard.

3. Controls on Present Permafrost Distribution in Svalbard

Permafrost is a purely thermal phenomenon that involves ground temperatures not exceeding 0°C for two continuous years (French 1996). Air temperature, topography, snow cover, wind, lithology, geothermal heat flow and distance to ocean are among the main factors in the distribution and thickness of permafrost on islands such as the Svalbard archipelago. Many of these factors are covered by the concept "topoclimate". This embraces all the complexities when ground surface climate is considered, rather than air climate. Primary influences on topoclimate include elevation, aspect, slope angle, vegetation cover, and the material making up the near-surface layer. In cold climates, a central role is also played by the seasonal snow cover in influencing both ground temperatures and ground moisture regimes (Ballan- tyne 1978). While recognizing their complexity, the direct effect of some of these variables is out- lined below.

In the Svalbard context, in contrast to many lowland permafrost areas, topography is especially important as it relates both to differences in altitude and aspect. At high altitudes permafrost is usually thicker than in major valleys, as is demonstrated by mining activities (Liestøl 1976). This is partly due to lower air temperatures at higher altitudes, and partly due to enhanced cooling of mountain ridges or other topographic highs. Top- ographic-induced shadow in valleys may counteract this effect to some degree. Lithology is a control on geothermal heat flow, representing a major control on permafrost thickness. In Svalbard, below the depth of zero annual amplitude (15 - 20 m), the ground temperature increases by about 2 - 3 °C per 100 m (Liestøl 1976; Isaksen, Vonder Mühll et al. 2000).

Low air temperature is important to keep the ground from thawing. From an empirical point of view, the mean annual air temperature usually has to be below –2 °C to initiate widespread growth of permafrost (French 1996). Seasonal variations of temperatures are also important. Wind is also of importance as it determines where insulating snow accumulates during the winter and where the ground surface is kept free of snow. Beneath thick snow accumulations (or glaciers) permafrost is usually either shallow or even absent. The seasonal snow cover may also represent a source for soil moisture, which influences the thermal characteristics of the active layer downslope of snow accumulations (Humlum 1998). Variations in the timing and duration of seasonal snow cover are critical to the ground thermal regime because they change surface conditions and the associated ground surface energy balance.

Snow cover also has a direct effect on the distribution of permafrost on a local scale in Svalbard. In the central, more arid parts of Spitsbergen the average winter snow cover is thin and the ground surface cools efficiently during the winter. By contrast, in the more maritime western and eastern parts, the snow cover is thicker (Humlum 2002; Hagen et al. 2003) and therefore reduces heat loss from the ground surface during winter. Especially in the eastern and southern parts of the archipelago, considerable amounts of snow may accumulate on the landscape by snow- drift derived from upwind sea ice areas (Humlum 2002). Interannual variations in the establishment of the snow cover are also important. A dry and cold autumn enables enhanced cooling of the active layer and topmost permafrost. High snowfall during late winter and late onset of snow melt protect the ground against thawing in early summer. The combination of these two meteorological phenomena is beneficial for the conservation and growth of permafrost, as recently exemplified by the winter 2002/03. Variations in the timing and duration of seasonal snow cover presumably also have an influence on active layer thickness, but the effect is still not known in detail (Christiansen et al. 2003).

Distance to the ocean or other major water bodies is also important, as water bodies repre- sent a major source of heat. Permafrost is there- fore shallow (100 m) close to the shore. Also, thermal effects of major lakes or rivers may be considerable, tending to reduce permafrost thickness below or near such water bodies.

4. A Long-term Perspective on Permafrost in the Arctic

Polar climate today is cold and permafrost widespread, but this has not always been the case. The record of global climate variations during the Phanerozoic (past 545 My), based on temporal and spatial patterns of climate sensitive sedimentary indicators (Shaviv & Veizer 2003), shows intervals of tens of millions of years duration, characterized by predominantly colder or predominantly warmer episodes, called icehouses and greenhouses (Frakes et al. 1992), respectively. Growing evidence, such as the correlations between palaeoclimate records and solar and cosmic ray activity indicators (e.g. 10Be, 14C), suggests that extraterrestrial phenomena are important drivers for climatic variability on time scales ranging from days to millennia (Friis- Christensen & Lassen 1991; Tinsley & Deen 1991; Soon et al. 1996; Svensmark 1998;

Soon et al. 2000; Björck et al. 2001; Bond et al. 2001; Pang & Yau 2002; Solanki 2002).

Reconstructions of Tertiary surface temperatures are still somewhat tentative. It is clear, how- ever, that the persistent cooling which ultimately led to the Quaternary glaciations did not commence until about 33 Mya, in Oli- gocene times (Zachos et al. 2001). The gradual closing of the connection between the Pacific and the Arctic Ocean by continental drift gradually reduced the previously effi- cient ocean heat transport from equatorial regions toward the North Pole, and the Northern Hemisphere experienced cooling. The Greenland ice sheet presumably formed about 7 Mya (Zachos et al. 2001). Formation of the first major permafrost regions at low altitudes was presumably contemporary with the first major glaciations.

Atmospheric chemical changes may have contribut- ed to the Tertiary cooling trend. Over geological time, the amount of atmospheric CO_2 rep- resents a balance between release by volcanic activity and rock metamor- phism, and uptake by bedrock weathering reactions. High rates of sea floor spreading are associated with widespread active volcanism, orogenesis and rock metamorphism, leading to higher atmospheric CO_2 con- tent, resulting in warmer global climate. Conversely, in intervening periods of relatively low rates of sea floor spreading, uptake of atmospheric CO_2 by bedrock weathering processes dom- inate, and global climate consequently cools. The global cooling experienced following the Alpine orogenesis in Cretaceous and early Tertiary times may partly result from this (Summerfield 1983, 1991). In addition, geological mechanisms involving phases of regional uplift and ero- sion may also have been instrumental in the development towards cooler climate and permafrost growth (Japsen & Chalmers 2000).

Orbital influences were also important in Tertiary cool- ing (Milankovitch 1930, 1941; Imbrie

& Imbrie 1979; Imbrie et al. 1984; Miller et al. 1991). Marine stable isotope records show a strong 40 000 peri- odicity, consistent with a high latitude orbital (obliquity) control on global ice volume and temperature (Zachos et al. 1997). Orbital influences were also apparent at preces- sion and eccentricity frequencies, although not as clear as that derived from obliquity variations.

By 3.5 Mya, the climate of the Northern Hemisphere had cooled considerably, as reflected in the oxygen isotope record of marine cores (Ruddiman et al. 1986; Raymo 1992; Harris 2002). The stage was set for subse- quent massive Qua- ternary glaciations and widespread establishment of permafrost. The global cooling culmi- nated in a series of step-like, sudden, changes in climatic conditions over the last 2.6 My, and a series of recurrent

shifts between glacial and interglacial conditions began (Jansen & Sjøholm 1991). From interpretations of ocean cores and long sequenc- es of loess, it is apparent that no less than 30 - 40 glacial cycles have affected the Earth's surface during the Quaternary (Dansgaard & Tauber 1969; Kukla 1987; Imbrie et al. 1993). Very thick permafrost (1 - 1.5 km), such as found in unglaciated parts of Siberia, presumably grew through- out most of the Quaternary.

5. Age of Svalbard Permafrost

In Svalbard, permafrost is typically is about 100 m thick in major valley bottoms and up to about 400 - 500 m thick in the high mountains (Liestøl 1976).

During the Weichselian period most of Svalbard was covered by thick glacial ice. Opinions differ as to the size and extent of the ice cover. Glacial striae in several main valleys suggest that Weichselian glaciers grew to suffi- cient thickness to reach the pressure melting point at the glacier sole, enabling basal sliding, even though surface air temperatures at that time were probably significantly below present values. During the Weichselian, pre-exist- ing permafrost in deep valleys would have been exposed to thaw both from above (frictional heat generated by bas- al glacier sliding) and below (geothermal heat). Adopting typical values for both frictional heat generated by glacier sliding and geothermal heat flow; the combined effect would have been the thaw of about 1 cm of permafrost per year (Weertman 1969). A typical glacial period is about 100 Ky long, but only for shorter periods does a signifi- cant glacier cover grow to large (continental) size. Taking 30 Ky as an order of magnitude for the duration of exten- sive glaciation in the Svalbard region, this would generate a thaw of about 300 m of permafrost during the Weichse- lian. If surging glaciers or rapid ice streams occurred in Svalbard during the Weichselian, energy dissipated by glacier sliding would have caused additional thawing of permafrost beneath valleys affected by such glaciers. This signals that, while permafrost in the main trunk valleys may have been eliminated during many Quaternary glaci- ations, some of the permafrost found beneath the highest elevations may be of considerable antiquity, perhaps as much as 700 Ky. Depending on Weichselian maximum ice extension and thickness, some permafrost in the western coastal regions of Svalbard may also be of pre-Holocene age where the existence of ice-free areas have recently been demonstrated (Landvik et al. 2003).

A late Holocene age of permafrost near present sea lev- el in central Spitsbergen is indicated by the dating of both pingo and ice wedge initiation (Svensson 1971; Jeppesen 2001). Ronnert & Landvik (1993), working at the glacier Albrechtbreen, on Edgeoya, suggested from lithological

differences between moraine ridges, that the first ice advance following the early Holocene warm period occurred during a period with limited permafrost, whereas permafrost was more extensive during the subsequent glacier advance during the Little Ice Age.

6. Svalbard Permafrost Compared to Other Permafrost Areas

Today glaciers cover ca. 60 % of the total land area of Svalbard, leaving 40 % to the periglacial environment and permafrost. This amounts to a permafrost surface area of about 25 000 km^2. Thus, Svalbard represents the largest permafrost area in Europe outside of Russia.

In contrast to some other regions with extensive permafrost, such as Siberia and northern Alaska, much permafrost in Svalbard is presumably of young (i.e. Holocene) age. It tends to have been thawed during the recurrent Quaternary glaciations. High altitude permafrost in Svalbard may represent an exception to this. Another contrast between Svalbard permafrost and extensive lowland permafrost lies in the surface relief. In Svalbard the mountain topography introduces local, large variations in ground temperature regime and permafrost thickness due to variations in slope, aspect, altitude, topographic shading and redistribution of the winter snow cover by wind. As a result, permafrost in Svalbard is presumably more sensitive to changes in temperature and thickness than is the permafrost of extensive low- lands in Siberia, northern Canada and Alaska. In addition, Svalbard is an archipelago located near the northernmost branches of the North Atlantic Current and the southern limit of polar pack ice. Even small variations in these important phenomena will induce rapid climatic variations with potential effects on the local Svalbard climate and permafrost not known from more continental permafrost regions.

7. Svalbard Geomorphic Permafrost Phenomena

7.1 Pingos

Pingos represent a typical permafrost phenomenon in Svalbard. The majority of pingos are found below the uppermost Holocene marine limit. They are formed by aggradation of perma- frost in association with ice lensing or freezing of massive ice bodies within near-surface sediments. Intrusive ice or injection ice may form in two ways. First, water expelled ahead of the freezing front during freezing of coarse sediments may be intruded into adjacent unfrozen sediments, where it eventually freezes to form a massive body of ground ice. Second, sub-permafrost groundwater in areas of discontinuous permafrost may be injected under artesian pressure into unfrozen

sediment. Subsequent freezing of the injected water again leads to the development of massive ground ice. In either case the resulting ice body may cause local lifting of the ground surface and the growth of a hill, called a pingo (local Inuit [Mackenzie Delta, Canada] name for hill or mound).

Pingos are generally circular or oval in plan. In Svalbard, they may achieve a horizontal extension of up to 500 m and heights of up to 40 m. Pingos develop in bedrock and a variety of unconsoli- dated sediments, including till, slope deposits and alluvial silt, sand and gravel (Liestøl 1976). Pingos resulting from water expulsion during permafrost aggradation are termed closed-system pingos (Mackay 1972), while those fed by sub- permafrost groundwater percolation are known as open-system pingos (Müller 1959). Most, if not all, pingos in Svalbard are of the open-system type (Liestøl 1976).

Many open-system pingos in Svalbard occur at or near the transition between slope sediments and valley-fill deposits (Liestøl 1996). Another typical location for open-system pingos in Svalbard is along the lower border of late Holocene alluvial fans. During winter, any remaining unfrozen water presumably flows in the lower- most layers of such coarse-grained deposits, on top of more impermeable permafrost below, until reaching the lower limit of the alluvial fan. Here, the water is forced towards the surface as the alluvial deposits thin, and is consequently exposed to rapid cooling and freezing. At certain sites, the overlying sediments are lifted in sufficient thick- ness to protect against summer melting and an open-system pingo formed. During the winter, it is common to see icing blisters forming along the lower rim of alluvial fans. Such phenomena represent seasonal features only and disappear during the following summer.

Lakes in unconsolidated sediments are rare in Svalbard. They might explain the apparent absence of closed-system pingos in Svalbard. The situation has a partly glaciological explanation because Svalbard, during the Quaternary glaciations, was an area of net glacial erosion. Thus, extensive and thick deposits of unconsolidated sediments are absent. Likewise, late Holocene relative land submergence due to the Neoglaciation and the lack of extensive delta plains further deprives Svalbard of extensive low-relief sediment areas like those found at typical sites of closed-system pingo formation (e.g. Mackenzie and Lena River deltas).

Liestøl (1976) observed a particular relation- ship between glaciers and open-system pingos in Svalbard. Permafrost is largely continuous, but many glaciers have a subpolar thermal regime, so permafrost extends only beneath their marginal zones. Beneath the warm-based ice

in the central parts of glaciers, meltwater percolates into the unfrozen substrate and then migrates under hydrostatic pressure beneath the permafrost that underlies the glacier margins. In consequence, artesian pressures develop in sub-permafrost groundwater beyond the glacier margins, allowing the growth of open-system pingos in areas of thinner or weaker permafrost, such as close to the lower limit of alluvial fans. Reindalen, in central Spitsbergen, represents the type locality for such open-system pingos and displays a variety of active pingos in different stages of growth. Following Liestøl's line of thought, periods of pingo growth in Svalbard may, to some degree, take place in concert with major glacier advances, leading to local reorganization of ground temperatures and hydrological characteristics.

7.2 Ice Wedges

A striking feature of many valley bottoms and sloping valley sides in Svalbard is the presence of polygonal networks formed by shallow troughs in the ground surface. These polygons range from 15 to 50 m in diameter and are found on all major islands in the archipelago. The surface troughs mark the locations of ice wedges that extend 3 - 5 m downwards into the permafrost from the base of the active layer. Such ice wedges result from the repeated opening of tension cracks caused by thermal-contraction cracking during winter.

Ice wedges consist of vein ice, and typically take the form of vertical wedge-shaped dykes penetrating downwards into the permafrost. In Svalbard they may be between 10 mm and 5 m wide and usually penetrate 2 - 5 m into the permafrost. Lachenbruch (1962) provided a detailed analysis of the mechanism of ice wedge formation, based on the contraction theory first pro- posed by Leffingwell (1915). Cracking results in a polygonal network of vertical cracks that relieve tensile stress set up by such contraction. Meltwater percolates into them during spring to refreeze, preventing the cracks from closing fully as the permafrost warms and expands in summer. Since the tensile strength of ice is less than that of frozen sediment, thermal contraction cracks tend to reopen along the pre-existing network of ice veins in subsequent winters. Ice wedges thereby grow incrementally as each successive phase of contraction cracking is accompanied by filling of the open crack with more ice.

The incremental growth of ice wedge produces foliation parallel to the sides of the wedge. Such foliation is due to aligned ice crystal fabrics and the incorporation of air bubbles and silt layers. Many ice wedges are typically 1 - 3 m wide and penetrate 3 - 5 m below the permafrost table. The polygons generally range from 15 m to 50 m

in diameter. Their plan form may be roughly hex- agonal with angles tending to approximate 120°, or orthogonal with a tendency towards 90° junctions.

In Svalbard, ice wedges have been observed mainly in large valleys such as Adventdalen, Colesdalen and Reindalen—all in central Spits- bergen—and Sassendalen, in southern Spits- bergen, but also at some sites in the uplands surrounding the valleys (Sørbel et al. 2000: Tolgensbakk et al. 2001). From the Adventdalen area, Sørbel & Tolgensbakk et al. (2001) and Sørbel et al. (2001) report that ice wedges are common, occurring on both flat terrain and on slopes up to 25º, and up to altitudes about 500 m a.s.l. Ice wedges above 250 m a.s.l. are typically developed in weathering material of Cretaceous age, where- as in the valley bottoms they are mainly found in fluvial or glaciofluvial sediments (Sørbel & Tol- gensbakk 2002).

Relatively little research has been carried out on Svalbard ice wedges. Svensson (1976) investigated ice wedges in Adventdalen in the summers of 1968 and 1972 and found evidence for the investigated ice wedges being active. He particularly noted that a small ice dome at that time was forming in the central cracking part of ice wedges, indicating that the active layer thickness has been thinning during the previous years. This development was explained partly by a lowering of the mean annual air temperature from –5.9 °C prior to 1968 and to –6.3 °C in 1972. Matsuoka (1999) reports similar phenomena observed at ice wedges in Adventdalen, based on two excavations carried out in 1992. He explained the secondary ice dome as having either grown along with loess deposition (i.e. syngenetic origin) or as reflecting an episodic thaw penetration several decades ago, presumably during the extraordinarily warm summers of 1922 and 1930 that followed the main 20th century warming event around 1920.

Thermal-contraction cracking at an ice wedge site in Adventdalen was monitored in the period 1990–92 (Matsuoka 1999). The amount of con- traction was found to be proportional to the mag- nitude of the minimum temperature. A maximum of 16 mm separation was measured over the ice wedge when a minimum winter ground surface temperature of –27.3 °C was registered, while the temperature at the permafrost table was –17.1 °C. Based on summer observations, Matsuoka (1999) reported a 15 % cracking frequency of ice wedges in the Adventdalen area.

Recently the O18 variation in three ice wedges in Adventdalen was analysed with respect to Late Holocene palaeoclimatic variations (Jeppesen 2001). A broadly similar isotope variation was found across the ice wedges, suggesting that Svalbard ice wedges may contain import- ant palaeoclimatic information. No direct dating of the

observed 18 variations was possible, but organic material found in the outer (older) part of one of the ice wedges yielded an age of about 2900 cal. yr BP using the 14C accelerated mass spectrometer technique (Jeppesen 2001). As the sample came from the outer part of the ice wedge, the age is interpreted as a maximum age of the ice vein containing the organic material; this indirectly provides the approximate maximum age of the ice wedge (Jeppesen 2001). This age cor- responds rather well with the maximum age of 2650 ± 55 yr BP from driftwood found on the top of the Longyearpingo (Svensson 1971), only 3 km from the ice wedge site investigated. It appears, therefore, that permafrost, pingos and ice wedges in the main valleys such as Adventdalen are about 3000 years old (Christiansen 2003). On the other hand, Sørbel & Tolgensbakk (2002) suggest that some of the ice wedges found at higher altitudes may be pre-Weichselian and could possibly have been preserved below cold-based ice.

7.3 Palsas

Palsas are permafrost peat mounds that usually occur in regions of discontinuous permafrost. They are not very frequent in High Arctic Sval- bard (Salvigsen 1977; Åkerman 1982), but are usually found in sub-Arctic permafrost areas such as northern Scandinavia. The typical palsa takes the form of a peat mound rising from the surface of a fen. Palsas are produced by down- ward freezing from the ground surface, enhanced by a thin snow cover on the palsa compared to the surroundings. Ice in palsas does not form solid bodies of ice, but only millimetre-thick lenses of ice. Their maximum dimensions are about 5 - 7 m high and 50 - 100 m across. Palsas in Svalbard are usually much smaller, only 0.5 - 1 m high. A few examples of palsas are found in lowermost Adventdalen in wet areas rich in vegetation.

7.4 Sorted Circles

Patterned ground in the form of 2- 10 m sorted circles represents active layer phenomena, and is widespread on level ground in Svalbard (e.g. Åkerman 1987; Etzelmüller & Sollid 1991). Sorted circles cover many mountain plateaus and coastal flats, signalling the presence of permafrost below, even though the detailed origin of patterned ground is not yet fully clear. Washburn (1956) was able to list no less than 19 different hypotheses for patterned ground development. Most scientists tend to agree, however, that patterned ground presumably arises due to the combined effect of frost-heave, thaw settlement, consolidation and differential movements due to recurrent growth and melting of small (segregated) ice lenses in the active layer. All these processes are frequently combined under the general heading of cryoturbation.

Fine examples of patterned ground (sorted cir- cles) are found at Kvadehuksletta, northwestern end of the Brøggerhalvøya peninsula at 79° N, 12° E. Tolgensbakk & Sollid (1987) mapped the geomorphology and Quaternary geology of this area. Fields of sorted circles occur especially in depressions between raised beach ridges, probably due to high soil water content and precense of fine-grained sediment, leading to an enhanced frost action environment (Etzelmüller & Sollid 1991). From detailed studies of the dynamics of well-developed sorted circles, Hallet & Prestrud (1986) and Hallet et al. (1988) conclude that motion in the sorted circles includes convection in fine-grained centre and "subduction" in the fine/coarse contact. A model for self-organization of sorted patterned ground has recently been pro- posed by Kessler & Werner (2003), drawing upon examples from Kvadehuksletta. Another fine example of sorted circles was reported by Jahn (1975) from Hornsund, in southern Spitsbergen. It is interesting to note that both Kvadehuksletta and the Hornsund site are dominated by weathering residuals of dolomite bedrock.

7.5 Rock Glaciers

Rock glaciers are characteristic large-scale flow features of frozen material in permafrost high- relief regions (Haeberli 1985; Barsch 1996; Humlum 1999; Isaksen 2001). They are located at the foot of rock-free faces with a high supply of talus and, when active, typically take the form of 20 - 100 m thick tongue- or lobe-shaped bodies with cascading frontal slopes standing at the angle of repose. Their length may be as much as several kilometres, but the typical length is 200 - 800 m measured parallel to the flow direction (Barsch 1996). The surface of rock glaciers is covered by coarse (0.2 - 5 m) rock fragments, and displays a 1 - 5 m high curving transverse furrow-and-ridge topography. Active rock glaciers typically flow downslope 0.1 - 1 m per year (see e.g. Barsch 1996), that is, they are more sluggish than normal glaciers. Active rock glaciers are often seen as characteristic of continental environments, although a significant number of rock glaciers have been described from maritime regions as well (e.g. Sollid & Sørbel 1992; Humlum 2000). The topographic and meteorological controls on rock glacier initiation and growth are still not known in detail, and a long-standing discussion on rock glacier origin, internal structure, rheology and nomenclature has originated from this lack of field knowledge. Most scientists agree that rock glaciers are the result of a localized, large supply of talus in a permafrost environment. In addition, rock glaciers represent a highly efficient transport system of

weathered debris in high- relief, cold climate regions (Humlum 2000).

Rock glaciers of different morphological type are widespread in Svalbard (e.g. Sollid & Sørbel 1992; André 1994; Berthling et al. 1998; Isak- sen, Ødegård et al. 2000; Isaksen 2001; Kors- gaard 2002), and many of these conspicuous land- forms presumably derive from accumulation of avalanche snow on talus sheets, giving rise to aggrading permafrost consisting of a mixture of ice and rock fragments (Liestøl 1962). An aerial photograph inventory of Svalbard rock glaciers (Kristiansen & Sollid 1986) revealed the existence of more than 500 rock glaciers. Many are found in coastal areas, situated below the escarpment that delimits the inner part of the strandflat. Rock glaciers are particularly frequent along the extreme western and northern coast of the largest island, Spitsbergen, and on Prins Karls Forland, a small island off western Spitsbergen (Sollid & Sørbel 1992). Svalbard rock glaciers are generally less than 60 m thick and less than 500 m long. The permafrost base is presumably far beneath the base of these features, as permafrost thickness is estimated to vary from about 100 m near the coasts to more than 450 m in mountain areas (Liestøl 1976).

Surface velocities of Svalbard rock glaciers are known to range from no significant movement to 10 cm/year (Sollid & Sørbel 1992; Isaksen, Ødegård et al. 2000; Kääb et al. 2002). Measurements from talus-derived rock glaciers on Prins Karls Forland show that most surface velocities are within the range of 1 - 4 cm/year based on carrier-phase differential GPS measurements (Berthling et al. 2001).

The age of Svalbard rock glaciers is not known in detail and current age estimates of Svalbard rock glaciers are therefore coupled to the Late Weichselian glacial history. The maximum extent of the Svalbard Weichselian ice cover, especially along the west coast of Spitsbergen, has been a matter of debate. A recent reconstruction of the Late Weichselian maximum ice sheet suggests more than 800 m of Weichselian ice cover at Prins Karls Forland and the west coast of Spits- bergen (Landvik et al. 1998). In contrast, another study from central Prins Karls Forland (Anders- son et al. 1999) presents evidence of a much more limited expansion of local glaciers during the Late Weichselian.

These findings introduce uncertainty about the age and possible onset of rock glacier development in the outermost western part of the archipelago. In addition, there is uncertainty regarding the extension of permafrost at low altitudes during the Holocene climatic optimum. It has been suggested that most rock glaciers proba- bly started to develop at the onset of Holocene, and that even older

forms cannot be ruled out (Sollid & Sørbel 1992; Kääb et al. 2002). Some very large rock glaciers are apparently located in areas that may have been ice-free for a long period, perhaps as much as 40 Ky. Western Prince Karls Forland is one such location. Here, some of the largest rock glaciers in all Svalbard are found (Liestøl 1962; Berthling et al. 1998; Berthling et al. 2000). However, André (1994), based on lichenometry, suggested that rock glacier formation in the Kongsfjorden area, north-west Spitsbergen, started ca. 3500 BP, while Isaksen, Ødegård et al. (2000) estimated the age of the surface mate- rial at the terminus of Hiorthfjellet rock glacier, central Spitsbergen, to about 4000 BP. This age estimate was based on the length/surface velocity ratio, assuming constant flow velocity since rock glacier initiation. Finally, existing knowledge on Holocene climate in the Svalbard region (see e.g. Salvigsen et al. 1992; Svendsen & Magnerud 1997; Snyder et al. 2000) support a late Holocene aggradation of permafrost at low altitudes and subsequent formation of several Svalbard rock glaciers. A detailed understanding of the onset of rock glacier formation in Svalbard, however, remains slightly elusive and awaits further research.

8. Permafrost Engineering

A structure placed on, or in, permafrost in Sval-bard will alter the heat exchange between the ground and the atmosphere and will, in most cases, result in increased heat flow from the atmosphere to the soil. Removal of the organic layer for the foundation construction and snow accumulation around, under and adjacent to the structure, and heating of the structure may enhance this effect. The physical and mechanical properties of permafrost are generally temperature dependent and this effect is most pronounced at temperatures within 1 or 2 °C of thawing (Ladanyi et al. 1996). Increases in permafrost temperature will, in general, lead to deteriorating strength and defor- mation characteristics, potential accelerated settlements and possible foundation failure (see Instanes 2003). It is of para- mount importance, therefore, that an evaluation of the thermal effect of an engineering structure is taken into account in planning, design, construction and maintenance of structures in Sval-bard and in the Arctic in general.

Most of the engineering concerns related to the design of infrastructure on ice-rich permafrost can be classified into those related to increases in permafrost temperatures, increases in the active layer thickness (annual thaw depth) and degradation of permafrost.

Warming of permafrost at depth will cause an increase in the creep rate of existing foundations such as piles and footings, increased creep of embankment foundations and eventual loss of adfreeze bond support for piling. Increas-

es in annual thaw (active layer) will cause increased thaw settlements during seasonal thaw- ing, increased frost-heave forces on pilings and increased total and differential frost heaving during winter. Development of residual thaw zones (taliks) will cause decrease of effective length of piling in permafrost, progressive landslide movements and progressive surface settlements (Esch & Osterkamp 1990).

Design of foundations in permafrost regions must, therefore, always include an evaluation of the maximum active layer thickness and the permafrost temperature the foundation soils will experience during the lifetime of the structure. The initial and long-term bearing capacity of the foundation can then be determined (Instanes 2003).

9. Conclusions

In contrast to many other regions with extensive permafrost, e.g. Siberia and northern Alaska, much of the present permafrost at low altitudes at least in central Svalbard is presumably of young (i.e. Late Holocene) age. It probably thawed, at least in the major valleys, during the recurrent Quaternary glaciations. High altitude perma-frost in Svalbard may represent an exception to this and may be of some antiquity. In Svalbard, topography introduces local and large variations in ground temperature regime and perma-frost thickness. This is due to variations in slope, aspect, altitude, topographic shading and redistribution of the winter snow cover by wind. As such, permafrost in Svalbard is highly prone to temperature and thickness changes when compared to permafrost in the northern lowlands of Siberia, Canada and Alaska.

Svalbard is a relatively small land area located near both the northernmost branches of the North Atlantic Current and the southern limit of polar pack ice. Even small variations in these impor- tant phenomena induce significant effects on the local Svalbard climate and permafrost that are not known from more continental permafrost regions.

From an engineering point of view, any future warming of permafrost may cause increases in creep rates of existing foundations such as piles and footings, increased creep of embankment foundations and eventual loss of adfreeze bond support for pilings. Increases in annual thaw (active layer) will cause increased thaw settlements during seasonal thawing, increased frost- heave forces on pilings and increased total and differential frost heaving during winter. It has proven possible to construct roads on glaciers in permafrost areas, provided an artificial road embankment with a minimum thickness corresponding to the local active layer thickness for identical material is established. However, this solution leads over time to increasing alti- tude difference between the road and the adjoining glacier surface, and ultimately, to problems of slope failure.

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