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Late Quaternary accretion and decline of syngenetic ice-rich permafrost

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The region of perennially frozen ground constitutes one quarter of the northern hemisphere landmass. Negative annual mean air temperatures and ground freezing periods exceeding ground thaw periods are the prerequisites for downward freezing of loose deposits and bedrock in non-glaciated regions. Hence, permafrost distribution and thickness on Earth are closely related to late Quaternary climate variations and ecosystem modifications. Generally, glacial stages are expected to promote permafrost accretion and ground ice formation in accumulating sediments, whereas interglacial stages lead to intense permafrost thaw and ground-ice melt.

Deep freezing synchronous with ongoing sedimentation is termed as syngenetic while epigenetic freezing occurs in pre-existing deposits. Typical landforms of syngenetic permafrost are ice-wedge polygons of past tundra environments. Ice-rich silty and/or peaty deposits intersected by large ice wedges (up to several decameters in height and meters in with) build-up unique Ice Complex (IC) strata, which are aligned to mid- and late Pleistocene stadial and interstadial stages. The most prominent example for such formations is the Yedoma IC of MIS 3 interstadial age. Increasing air and ground temperatures during warm stages disturbed the thermal equilibrium at the upper permafrost boundary and subsequently led to permafrost thaw, ground-ice melt and surface subsidence. Typical permafrost degradation processes are thermokarst and thermo-erosion that result in large lake-filled basins (up to kilometers in diameter) and valley structures, respectively.

The modern periglacial surface in Alaskan and East Siberian lowlands preserves Yedoma IC remnants in uplands and hills next to widely-distributed thermokarst basins since lateglacial and Holocene warming affected up to 70% of the original IC distribution on an area of more than 1,000,000 km2.

The overarching climate-driven pattern of cold-stage IC permafrost accretion and warm-stage IC permafrost degradation provides, however, only a first-order approximation in understanding past permafrost dynamics. Beside long-term freezing conditions also thin snow cover and winter precipitation were required to create ice-rich permafrost such as Yedoma IC. Its dynamics are furthermore altered by on-site conditions in water supply, relief and vegetation, which promote either aggradation or degradation processes. For example, current climate warming certainly enables large-scale permafrost thaw and widespread thermokarst. But, ice-wedge growth and permafrost accretion occurs in places after local disturbance such as thermokarst lake drainage causing a change from lacustrine to palustrine environments. Repeated occupation of thermokarst basins by lakes is commonly described as thaw-lake cycle although hereditary structures, i.e. pre-existing basins promote the lacustrine refill and highlight the path-dependence of thermokarst processes and the importance of the paleo-relief.

Traces of periglacial landforms preserved in permafrost deposits are indicative of the interplay between past climate and landscape settings. Besides climate control on-site periglacial morphology, hydrology and vegetation alter permafrost regimes, and are to be taken into account when interpreting late Quaternary permafrost chronologies. In summary, the completeness of certain vertical permafrost sequences depends (1) on paleo-relief that defined past accumulation and (thermo-)erosion areas, and (2) on overprints of degradation periods that erased older formations.