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Permafrost as palaeo-environmental archive – potentials and limitations

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Since 1994, the Periglacial Research Group of the Alfred Wegener Institute is studying permafrost sequences of the Beringian landmass. The study sites in Siberia cover lake banks on Taymyr Peninsula, coastal sites at the Laptev and the East Siberian Seas, locations in the Lena Delta, at the lower Kolyma river, the middle Lena and the lower Aldan rivers, and the catchment area of the El'gygytgyn crater lake in Chukotka. In Alaska, permafrost tunnels near Fairbanks and Barrow, and coastal sites on the Seward Peninsula coast were studied. In addition, Canadian sites on Herschel Island in the Beaufort Sea and at the adjacent coast of the Yukon plain were studied.

Subsurface exposures like tunnels and cellars provided the opportunity for three-dimensional studies of sedimentary and ground ice features, relatively 'clean' field conditions for in-situ experiments, monitoring procedures, and detailed and repeatable sampling. Permafrost cores were drilled in order to study inaccessible sequences below the terrain surface and shelf sea floor. Cores were transported and stored frozen for further high-resolution analysis. Reference core sections were preserved for subsequent later studies. Terrestrial sediment cores are highly localized records, sometimes problematic in extrapolating horizons in inhomogeneous sediments like ground ice-deformed permafrost deposits, and drill campaigns are usually cost intensive and logistical challenging. Coastal permafrost cliffs often naturally expose large cross sections trough modern and ancient landscapes. Contrary to cores, they provide an opportunity to study the wider context of depositional environments and ground ice features. Due to the relative easy access to coasts and the recurring natural exposure of cliffs by thermo-abrasive wave action they are very convenient study objects for regional comparisons and correlation of past environmental conditions. Finally, palaeogeographical reconstructions are also guided by remote sensing-based analyses of geomorphological surface patterns, like Yedoma hills, thermokarst depressions, pingos or thermoerosional valleys.

We generally relied on a multidisciplinary approach to study permafrost sequences in order to use the rich palaeo-environmental information stored in these frozen records. Cryofacies analysis describes both sediment and ice structures that allow interpretation of freezing conditions, thaw events, temperature regimes, and the local accumulation conditions. Ground ice bodies were sampled by ice screw and chain saw for analysis of hydrochemical and stable isotope composition. Several ground ice types were classified. The interaction between ice, sediment, and cryosoil were determined. The isotope signatures of sub-vertically layered ice wedges contain information about temperature variations, evaporation conditions and precipitation sources during different periods of ice wedge formation.

The stratigraphy of the permafrost sequences was determined by lithostratigraphical classifications and geochronological results. Numerous sediment parameters were measured for differentiation between horizons in individual exposures, for local and regional stratigraphic correlation of permafrost sequences as well as for reconstruction of accumulation and transport conditions. Age determinations were carried out by radiocarbon analyses on organic remains, isochron uranium–thorium disequilibria technique on peats, optical stimulated luminescence on clastic sediments, and 36Cl/Cl stable isotope ratios measurements in ground ice.

For palaeo-ecological reconstructions various fossil bioindicators were studied including pollen, plant macro-remains, insects, ostracods, testate amoebae, diatoms, chironomids, and mammal bones of the so-called mammoth fauna. By combining these data sets, we assembled a complex picture of the climate, landscape and vegetation dynamics of the studied regions during the Quaternary past. Derived palaeo-information includes mean annual air temperatures, mean winter temperatures, mean Juli temperatures, precipitation, humidity, soil climate and chemistry, hydrology and hydrochemistry of waters).

The general potential of permafrost archives includes spatial (circumarctic, high arctic to boreal zones) and temporal (Mid Pleistocene to modern) environmental gradients. Lateral cross sections contain information about permafrost degradation during interglacial periods, the aggradation of ice-rich sequences during stadial and interstadial periods, and extreme changes in periglacial hydrology during the late Quaternary. The spatial reconstruction of ancient landscapes is possible by detailed study of kilometer-long coastal exposures. Temporally relative high resolution (about 50 years) isotope data from ice wedges reflect the Late Pleistocene to Holocene climate transition. Using transfer functions for pollen, plant macro remains or chironomids, the numerical estimation of palaeo-climate data (temperature and precipitation) is possible.

The limitations of permafrost archives are the frequent lack of continuous sequences due to thermokarst or thermo-erosion events. Local stratigraphies are sometimes difficult to correlate on a regional scale because of permafrost degradation and neotectonic influence on the accumulative/erosive environment in some regions. Until now there are still uncertainties for comparing different geochronological methods, some of them related to unknown influences of permafrost processes on chemical and physical parameters important to the age determination technique. Due to strong cryoturbation patterns and sometimes challenging sampling situations on near-vertical frozen exposures the geochronological resolution in permafrost sequences is usually lower than in lacustrine sequences or glacial ice cores. Eventually, as for any other archive, we need to consider the effect of local versus regional signals derived from the palaeo-ecological interpretation of fossil records.