Pedogenesis under permafrost and active volcanism in Southern Kamchatka – new aspects about the last glaciation

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ABSTRACT: Extent of glaciation and interpretation of morphostratigraphical findings remains difficult in tectonically active areas that are furthermore influenced by permafrost. Permafrost-affected soils on Quaternary deposits were sampled in southern Kamchatka to get information about soil development under permafrost conditions, and to further enlighten paleoenvironmental changes. All sites have permafrost induced hydromorphic properties and multiple layers of tephra. Pedogenesis is characterized using weathering indices and redistribution of iron. The soils are well developed despite of permafrost conditions. Two moraine complexes in the mountain valleys have minor differences in soil weathering, but different surface morphology. Both are of Late Pleistocene origin indicating an interstadial during MIS-2. Remains of glacial deposits at the west coast differ from the valley moraines by ice wedges and old tephra deposits (40 ka) indicating penultimate glaciation, or an extended stage during MIS-3 or MIS-4. The second corresponds to asynchronous Late Pleistocene glacial maxima in Japan and NE-Siberia.

1 INTRODUCTION

Kamchatka in Russia (Fig. 1) was glaciated during the Quaternary (Vlasov & Chemenkov 1950; Lapshin 1963; Mokrousov & Sadovskiy 1964; Geptner et al. 1965; Kraevaya et al. 1983). Four glaciations have been suggested so far. However, a detailed chronology about the landscape history is still uncertain. The Late Pleistocene period is well documented by distinct glacial and associated glaciofluvial valley sediments indicating the existence of at least two major glacial advances, called M1 and M2 (Braitseva et al. 1968). It is not clear if they are equivalent to early and late advances of the last glaciation, or if they represent two different glaciations. Furthermore, it is not clear if remains of glacial deposits at the west coast are of corresponding age to the M1 valley deposits, or if they represent a separate glaciation.

The aim of this study is to answer the question: is information about the landscape history preserved in permafrost-affected soils even during short fluctuations in climate, and whether or not it is possible to use the extent of soil development to estimate the relative chronology of glacial/glaciofluvial deposition in such cold environment, that in addition is influenced by volcanism.

2 MATERIALS AND METHODS

2.1 Study sites

The study sites are located in southern Kamchatka: the upper part of the Plotnikova valley between the Natschikinskoje Lake and the village of Natschiki about 70 km west of Petropavlovsk-Kamchatskiy (A in Fig. 1), the western foothills of the Balaganchik range (B in Fig. 1), and the west coast near Ust-Bolscheretsk (C in Fig. 1). Except for the coastal areas, mean annual temperatures are below 0°C, and precipitation varies between 700 and 1400 mm depending on altitude and aspect.

The mountains surrounding the working areas A and B reach between 1000–1500 m asl. A prominent glacial complex characterizes the valleys at about 280–360 m asl associated with terminal and lateral moraines and dead ice kettles, which is designed as M2. Down the valley at about 260–300 m asl, an older...
moraine complex, designated M1, follows. In contrast to the M2 deposits this M1 complex has a smooth topography and lacks typical moraine surface features. Both complexes are correlated with glaciofluvial terraces, T1 and T2, which occur 20 m and 7–8 m above the present valley floor, respectively (Braitseva et al. 1968). Only remnants of the T1 terrace can be found, whereas the T2 terrace is well preserved. Betula ermani forests cover the glacial deposits. No other moraines could be identified further down the valley except for remnants of glacial deposits at the west coast near Ust-Bolscheretsk (C in Fig. 1). These deposits are characterised by pronounced ice wedges in contrast to the M2/T2 and M1/T1 valley deposits. Glaciofluvial and fluvial deposits extensively fill the Apache basin between Balaganchik and the west coast. The lithologies of the glacial and glaciofluvial deposits have similar proportions of various igneous rocks (basalt, rhyolite, andesite, granodiorite, crystalline schists). Multiple layers of volcanic ash cover the whole area.

2.2 Methods

Bulk samples were collected from each horizon of the most strongly developed profiles on the crest of moraines and on terraces. Designation of horizon follows the US Soil Taxonomy (1999). To characterize the extent of soil weathering extractable iron compounds and weathering indices are used. All analyses were performed on fine fraction (<2 mm) of air-dried samples. Organic carbon (C$_{org}$) was measured by gas chromatography (ELEMENTAR vario EL). Soil pH was determined in 0.01 M CaCl$_2$ at a soil-solution ratio of 1:2.5. Cation exchange capacity (CEC) was measured in unbuffered 0.5 N NH$_4$Cl at a soil-solution ratio of 1:20 (Trüby & Aldinger 1985). Pedogenic Fe-oxides (Fe$_d$) were extracted by dithionite-citrate-bicarbonate (DCB) solution (Mehra & Jackson 1960). Non- or poorly crystallized Fe-oxides, hydroxides, and gels (Fe$_u$) were extracted by acid ammonium oxalate solution (Schwertmann 1964). Total element contents were determined by X-ray Fluorescence, and two weathering indices originally applied to silicate rock, were employed. Both methods have not been applied to permafrost environments so far. The Parker index describes the loss of alkali and alkaline earth elements during weathering (Parker 1970). As primary minerals resist weathering to different degrees, each ion is weighted by a factor to consider the strength of the element-oxygen-bond. The index should decrease with increasing soil development.

\[
Parker\ index = \left( \frac{Na}{0.35} + \frac{Mg}{0.9} + \frac{K}{0.25} + \frac{Ca}{0.7} \right) \quad (1)
\]

where X$_a$ = % element X/atomic weight of X.

Progressive weathering is further estimated by two molar group ratios (Kronberg & Nesbitt 1981):

\[
Index\ A = \left( \frac{SiO_2 + CaO + K_2O + Na_2O}{Al_2O_3 + SiO_2 + CaO + K_2O + Na_2O} \right) \quad (2)
\]

\[
Index\ B = \left( \frac{CaO + K_2O + Na_2O}{Al_2O_3 + CaO + K_2O + Na_2O} \right) \quad (3)
\]

The indices reflect the extent of silicate hydrolysis and the accumulation of Al-/Si-oxides by leaching of alkali and alkaline earth cations. The process involves the transformation of easily weatherable primary minerals to pedogenic minerals, formation of new products, release and eluviation of ions, and accumulation of residuals and pedogenic oxides during advanced weathering. Both indices decrease until Al- and Si-oxides dominate at the final stage of weathering. The indices can be applied to groups of soil horizons or soil profiles, thus enabling comparison of the degree of chemical weathering or relative age of the soil. The approach was applied and discussed in detail by Bäumler (2001) for a range of soils on different parent materials. The indices generally increase with depth in young in-situ weathered Holocene soils, and soils developed within short time scales of 10$^3$ years can be separated with confidence (Bäumler et al. 1996). The interpretation of the indices may be more complex due to heterogeneous parent material, or due to enrichment or depletion of particular elements by pedogenic processes like podzolization, clay migration, redox reactions, or salinization. To minimize these effects and to compare the different sites, weighted means were calculated for some of the parameters:

\[
X_m = \left( \frac{\sum(x_i d_i)}{\sum d_i} \right) \quad (4)
\]

where $X_m$ = weighted mean; $x_i$ = parameter x of horizon i; $d_i$ = depth of horizon i.

2.3 Tephrochronology

Multiple layers of volcanic ash cover all study sites. More than 20 marker tephras could be identified in southern and central Kamchatka (Braitseva et al. 1992, 1997). Except for site C on the west coast, all soils are covered by 4 of these marker tephras originating from the Kuril Lake Ilinskaya eruption around 7.8 ka BP, two eruptions of the Ksudach volcano 6 ka BP and around 1.8 ka BP, and the Opala eruption around 1.5 ka BP ($^{14}$C dating; Braitseva et al. 1992, 1997). The different tephra layers are generally weathered into two horizons, resulting in a series of weakly developed
cover soils over the buried subsoils, which formed partly in the active layer and partly in the perennial frozen glacial/glaciofluvial deposits. The permafrost table is located at 1.5–2 m below the soil surface except at site C. Older tephra deposits could not be identified except for remains of a white-colored tephra at the west coast overlying the till. It is thought to represent pyroclasts of a caldera eruption of the Opala volcano about 40 ka BP (O. Braitseva 1995, pers. comm.). The 40 ka old tephra was absent in the deposits of sites A and B.

3 RESULTS

The stratigraphy of the polygenetic soils with different tephra layers covering the partly frozen subsoils is exemplarily given in Figure 2 (sites B and C).

At site C the soil is classified as T ypic Haploturbel (US Soil Taxonomy 1999) or as a Gelic Cambisol (FAO 1994). All glacial and glaciofluvial deposits at sites A and B are covered with tephra from the Kuril Lake Ilinskaya, Ksudach and Opala volcano eruptions during the Holocene. At the west coast the moraines were additionally covered by lake sediments (Fig. 2) which were deposited during the formation of a graded shoreline between the caldera eruptions of the Opala volcano 40 ka BP and the Ksudach volcano 6 ka BP (Braitseva et al. 1968).

Due to permafrost all subsoil horizons are characterized by gleyic properties (redistribution of Fe) and cryogenic features (sorting and frost heaving), and the soils are classified as T ypic Haplorthels or as Gelic Andosols.

Up to 11% organic carbon was found in the buried A horizons of the tephra layers and in the underlying subsoils developed in the glacial/glaciofluvial deposits. In the non-buried topsoil A horizons organic carbon varied between 4.3% and 18.3%. Acidic pH (4.1–5.9) occurs throughout all sites with slightly higher pH in the subsoil horizons below the tephra deposits. There is no clear trend with soil depth. The differences are mainly due to stratification and parent material. The CEC vary between 0.6 and 67 cmol kg⁻¹ without any clear trend with soil depth. Ca was the dominant exchangeable cation in the soils at sites A and B, whereas Na was the dominant cation at site C. The non-pyroclastic subsoil horizons have reoxidimorphic (stagnic) features with depletion and non-cemented accumulation of Fe and Mn next to each other in the active layer (Bockheim et al. 1996; Swanson 1996). However, no indications of significant gains or losses of Fe, Mn or Al through translocation from the top horizons to the subsoil horizons or through lateral transport within the active layer during the summer months were found (e.g. E horizons or ferruginization over long distances). Dithionite- and oxalate-soluble Fe and Al strongly increase below Ksudach 1 tephra.

Figure 2. Stratigraphy of the soils at the Balaganchik range (site B) and the west coast (site C), South Kamchatka.
horizons having maxima in Ksudach 2 and Kuril Lake Ilinskaya tephra layers, and in the glacial and glaciofluvial deposits (Bäumler 2001). Soil depth concentration profiles of the different Fe forms are irregular throughout soil depth due to both the initial geochemistry of the parent materials and the influence of the active layer. Moreover, periods of weathering were obviously too short between tephra deposition to eliminate the primary geochemical signature of each tephra (Fig. 3).

Figure 4 gives an overview of the total amount of silicate-bound iron (Fe_{td}), well-crystallized iron oxides (Fe_{do}) and poorly crystallized iron compounds (Fe_{o}) in the uppermost subsoil horizon developed from glacial or glaciofluvial deposits below the ash cover.

The formation of well-crystallized iron oxides (Fe_{do}) is mainly a time-controlled process of aging of poorly crystallized forms. In profile T1a the results of the 5B3 horizon were used for comparison, but admixture from overlying tephra of the 5A5 horizon can not be excluded. There are only small differences between the M2 and M1 deposits, especially from the Balaganchik range (site B). The highest total amount of pedogenic oxides (Fe_{d}, Fe_{o}) are found in horizons developed in the oldest tephra and in the glacial/ glaciofluvial deposits. It indicates long periods of exposure at the surface before being covered by younger sediments. Absolute values up to 64 g kg^{-1} Fe_{d} and 40 g kg^{-1} Fe_{o} further indicate enhanced soil development. This might be unusual for permafrost conditions, if one assumes that permafrost was sustained throughout the Holocene since the last glaciation, and has not been described in the literature so far.

The weathering indices give clear trends indicating an increasing intensity of weathering from M2/T2 to M1/T1 deposits at sites A and B (Tab. 1). The results are similar if particular horizons are compared, e.g. the uppermost subsoil horizon of the glacial/glaciofluvial deposits, or if solum-weighted means of all subsoil horizons below the ash cover are calculated (equations 1 and 1 + 4, respectively).

The A (equation 2) and B (equation 3) indices shown in Figure 5 give similar results. The solum-weighted means calculated by equation 4 decrease from the parent materials to the M2/T2 soils, and finally to the M1/T1 soils. Decreasing indices indicate increasing

Table 1. Parker-index of the uppermost subsoil horizon (PI_{s}) and solum-weighted mean of all subsoil horizons (PI_{m}) below the oldest tephra layers (after equations 1 and 4).

<table>
<thead>
<tr>
<th>Site A</th>
<th>Site B</th>
<th>Site C</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2</td>
<td>M1a</td>
<td>M1b</td>
</tr>
<tr>
<td>PI_{s}</td>
<td>29</td>
<td>28</td>
</tr>
<tr>
<td>PI_{m}</td>
<td>35</td>
<td>30</td>
</tr>
</tbody>
</table>

Pl_{mean} of parent material: site A (glacial deposits) = 37, site A (glaciofluvial deposits) = 41, site B (glacial deposits) = 61, site C = 60.
extent of weathering (Bäumler 2001). The moraines at the west coast (site C) again do not fit. They are the least weathered soils in comparison to all other sites according to all indices despite the fact that these are the oldest glacial deposits (Braitseva et al. 1968). An influence of the permafrost induced hydromorphic properties, however, can be excluded, as Fe is not part of the equations 1–3, and as the mean annual temperatures are slightly above zero along the coastal areas.

4 DISCUSSION

Minor differences in the Fe fractions between the fossil soils of M2 and M1 at sites A and B indicate either minimal differences in soil age or a strong influence of the permafrost-induced redoximorphic features inhibiting aging or crystallization processes. The higher contents of Fe in the M1b, T1a and T1b subsoils are probably due to the more distinct redoximorphic features compared to M2. The small differences between M2/T2 and M1/T1 may therefore be the result of the cold climate, which may inhibit soil weathering. The difference in soil development, e.g. pedogenic Fe, between M2/T2 and M1/T1 at site A is most probably due to differences in sedimentation of the deposits (sorting) and distance from the source area. In addition, the glaciofluvial deposits at the valley bottom had been under the influence of high groundwater for longer periods compared to the moraine soils, also inhibiting soil weathering. There are only few studies on the development of soils of known age under such cold climatic conditions and influenced by permafrost and volcanic ash, for comparison. Tarnocai & Smith (1989) studied buried Pleistocene soils of known age in the central Yukon Territory, Canada, under recent permafrost. They showed that rubified Bt horizons were developed in interglacial soils, but not in Holocene soils. This was not observed in the buried subsoils of the valley deposits in South Kamchatka. It may indicate both, non-permafrost conditions during the last and the penultimate interglacial, and that the moraines and their corresponding terraces might be of Late Pleistocene age with slightly more advanced weathering of the M1/T1 soils indicative of an interstadial period.

There are possibly two reasons for the lower extent of soil development in the glacial deposits on the west coast. Sea spray comes along with a more or less continuous input of salts, especially of alkali and alkaline earth cations. It is shown by a relative amount of 21% Na at the exchange sites of the coastal soils compared to 4% Na in the soils of the valley deposits. This may assuage or even reverse the impact of weathering processes on the indices. Alternatively, the glacial drift was immediately covered by the lake sediments of >1 m depth, thus interrupting or strongly reducing chemical weathering.

The results fit well to new findings about the Pleistocene landscape history in the Japanese Alps (Aoki & Hasegawa 2001; Hasegawa 2001; Hirakawa et al. 2001) and Jakutia, NE Siberia (Siegert 2001, pers. comm., Siberia workshop, LMU München, 10/2002). In both regions the last glacial maximum was numerically dated 50–70 ka BP by 10Be exposure ages and tephrachronology. It was followed by a second maximum at around 30–35 ka BP, and by several minor advances starting 20–25 ka BP. Similar to southern Kamchatka only the oldest glacial deposits were characterized by pronounced ice wedges.

5 CONCLUSIONS

Polygenetic soils developed from Quaternary glacial and glaciofluvial valley deposits were studied with regard to the extent of chemical weathering. The subsoils are strongly influenced by permafrost and covered by multiple layers of volcanic ashes. The geochemistry of the soils allows differentiation into two levels of weathering reflecting different relative soil ages. Despite the cold climate and the influence of permafrost, soil development is enhanced compared to high mountain soils under similar climatic conditions in High Asia (Bäumler 2001). It may point to warmer periods during the Holocene, compared to recent conditions, than previously thought, as indicated by the soil development of the ash layers. Alternatively, it points to more or less continuously ongoing processes of weathering even across periods of lower temperatures. This is indicated by slight differences in the intensity of weathering between soils developed in the

Figure 5. Solumn-weighted mean of the A and B indices in the subsoil horizons developed from glacial or glaciofluvial deposits and weighted means of the corresponding parent materials.
deposits of M1/T1 and M2/T2 pointing to soil formation during an interstadial.

The glacial deposits on the west coast have ice-wedge casts and are covered by 40ka old tephra from the Opala volcano. Both features are absent at sites A and B in the valleys further to the east suggesting that the coastal and the valley deposits date from two different glaciations or from a clearly separated early and late advance during the last glaciation. The M1 or T1 deposits must be younger than 40ka unless the Opala tephra was blown to the west by strong winds, or completely eroded after deposition at M1 and T1. With respect to permafrost conditions, the extent of soil development, and the tephrochronology the results point to a last glacial maximum during MIS-4 represented by the glacial deposits at the west coast. The soils of M1 and T1 sediments have been developed during an interstadial period. The corresponding glacier advance probably represents the beginning or maximum of the temperature fluctuations during MIS-2, probably around 30–35ka BP, similar to Japan and NE Siberia. This is further indicated by the distinct morphological differences between M2 and M1. M2/T2, however, mark temperature fluctuations at the end of the last glaciation 10–20ka BP, separated from M1 by an interstadial period with more dry conditions.

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