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Basalt weathering in Central Siberia under permafrost conditions

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Abstract—Chemical weathering of basalts in the Putorana Plateau, Central Siberia, has been studied by combining chemical and mineralogical analysis of solids (rocks, soils, river sediments, and suspended matter) and fluid solution chemistry. Altogether, 70 large and small rivers, 30 soil pore waters and groundwaters and over 30 solids were sampled during July to August 2001. Analysis of multiannual data on discharge and chemical composition of several rivers of the region available from the Russian Hydrological Survey allowed rigorous estimation of mean annual major element concentrations, and dissolved and suspended fluxes associated with basalt weathering. For the rivers Tembenchi and Taimura that drain monolithologic basic volcanic rocks, the mean multiannual flux of total dissolved cations (TDS_c = Ca + Mg + Na + K) corrected for atmospheric input is 5.7 ± 0.5 t/km^2/yr. For the largest river Nizhniya Tunguska—draining essentially basic rocks—the TDS_c is 6.1 ± 1.5 t/km^2/yr. The overall CO_2 consumption flux associated with basalt weathering in the studied region (~700,000 km^2) achieves 0.08 × 10^{12} mol/yr, which represents only 2.6% of the total CO_2 consumption associated with basalt weathering at the Earth's surface. The fluxes of suspended matter were estimated as 3.1 ± 0.5, 9.0 ± 0.8, and 6.5 ± 2.0 t/km^2/yr for rivers Taimura, Eratchimo, and Nizhniya Tunguska, respectively. Based on chemical analyses of river solutes and suspended matter, the relative dissolved versus particulate annual transport of major components is $C_{inorg} \geq C_{org}$ > Na + K > Ca > Mg > Si > Fe ≥ Mn ≥ Ti ≥ Al which reflects the usual order of element mobility during weathering.

According to chemical and mineralogical soil and sediment analyses, alteration of basalt consists of (1) replacement of the original basaltic glass by Si-Al-Fe rich amorphous material, (2) mechanical desegregation and grinding of parent rocks, leading to accumulation of "primary" hydrothermal trioctahedral smectite, and (3) transformation of these trioctahedral (oxy)smectites and mixed-layer chlorite-smectite, into secondary dioctahedral smectite accompanied by removal of Ca, Mg, and Fe, and enrichment in Al. No vertical chemical differentiation of fluid and solid phases within the soil profile was identified. All sampled soil pore waters and groundwaters were found to be close to equilibrium with respect to chalcedony, gibbsite, halloysite, and allophanes, but strongly supersaturated with respect to goethite, nontronite, and montmorillonite.

Over the annual cycle, the contribution of atmospheric precipitation, permafrost melting, underground reservoirs, litter degradation, and rock and soil mineral weathering for the overall TDS_c transport in the largest river of the region (Nizhniya Tunguska) is 9.3 ± 3, 10 ± 5, 10.5 ± 5, 25 ± 20, and 45 ± 30%, respectively. In the summertime, direct contribution of rocks and soil mineral weathering via solid/fluid interaction does not exceed 20%. The main unknown factors of element mobilization from basalt to the river is litter degradation in the upper soil horizon and parameters of element turnover in the vegetation.

1. INTRODUCTION

Chemical weathering of silicate rocks is considered to be the principal process removing carbon dioxide from the atmosphere on long timescales (Berner, 1992), with the alteration of continental basalts accounting for ~30% of CO_2 total consumption (Dupré et al., 2003). As a result, numerous studies have been devoted to characterizing basalt weathering both from the analysis of soils and rocks, and from river solution chemistry (Nesbitt and Wilson, 1992; Gislason et al., 1996; Stefansson and Gislason, 2001 and references therein). These studies allowed the extraction of a quantitative picture of basalt weathering in various climates and determined the major factors controlling the intensity of chemical weathering. Runoff, temperature, rock mineralogy, and vegetation have been listed among the most important parameters governing the overall chemical erosion of basalts (Benedetti et al., 1994; Drever, 1994; White and Blum, 1995; Gislason et al., 1996; Brady et al., 1999; Moulton et al., 2000; Dessert et al., 2001; Hinsinger et al., 2001; Dessert et al., 2003). Among different world regions, cold boreal zones have been studied only in Iceland (Gislason et al., 1996) and the Columbia Plateau (Dessert et al., 2003). Because of their small areas, these regions only weakly contribute to the overall continental basalt weathering and associated CO_2 consumption. Large boreal regions such as Central Siberia are likely to play a more important role because they offer extensive surface to weathering and they are overlaid by organic-rich permafrost soils and wetlands that constitute important carbon sink (Botch et al., 1995). Moreover, the behavior of chemical elements in the course of permafrost thawing and organic carbon mobilization induced by global warming are key environmental issues related to these regions (Guo et al., 2004). The increase of river discharge and the unfrozen layer thickness in the Russian Arctic over the past several decades (Peterson et al., 2002; Serreze et al., 2002; Oelke et al., 2003) have provoked the release of

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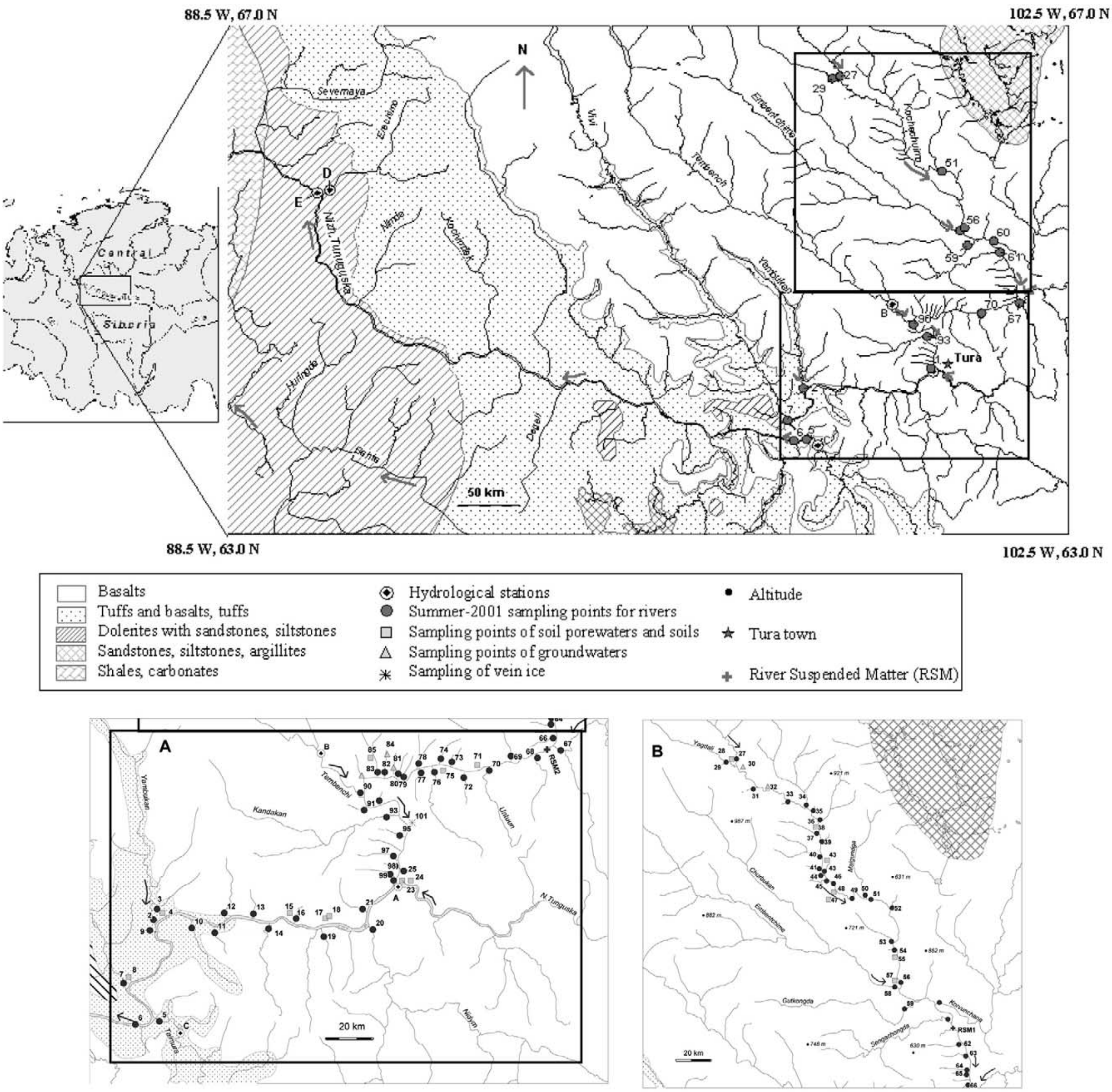

Fig. 1. Map of the area showing the rivers, hydrological stations, sampling points and geological situation. Sectors A and B.

carbon and metals trapped in the permafrost ice, which is likely to increase the fluxes of chemical elements to the ocean as well as to change their aqueous speciation and bioavailability. However, detailed studies of basalt weathering under boreal permafrost-dominated conditions are still lacking. To fill this gap, we have collected in the Nizhniya Tunguska river system (Yenisey Basin, Central Siberia, Fig. 1) over 100 samples of rivers, soil pore waters, and groundwaters, as well as soils, river suspended matter, and bed sediments. This region presents a unique opportunity for studying basalt weathering on a large scale because it combines homogeneously distributed soils and evenly developed vegetation over almost monolithologic terrains without any influence of industrial and agricultural activity (population density is less than 1 inhabitant/km^2), which allows us to consider that weathering occurs in a truly pristine area. Analyses of collected samples, combined with the long-term (1965–1975) data obtained from the Russian Hydrological Survey, provided a new picture of discharge and chemical composition of rivers draining monolithologic basaltic terrain, on short- and long-term scale. Building on this information and an original set of data, the purpose of this study is twofold. The first goal is a rigorous estimation of chemical elements and suspended matter fluxes for basaltic watersheds of various sizes and establishing the relative mobility of chemical elements during weathering. The second goal is to distinguish between the following possible sources of elements in river waters over the annual cycle and different seasons: fresh rocks, soils, vegetation litter and the permafrost ice, and underground reservoirs.