Present chemical weathering of basalt in Iceland

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Introduction

Before the initiation of the water cycle on the 'early Earth' all the rocks were volcanogenic (e.g. Ronov, 1964). At present, volcanic rocks cover about 8 % of the land surface of the Earth and more than half of that is of basaltic composition (Meybeck, 1987). The present contribution of the weathering of volcanic rocks to the dissolved load of the world's rivers is less than 3%, the most important contribution comes from carbonate rocks (45%) and shale (20%; Meybeck, 1987). The high contribution of shale is primarily due to the weathering of small portions of the shale, i.e. calcareous- and pyritic-shales. The chemical weathering of Ca-Mg silicate rocks is important for the atmospheric CO_2 on a multimillion-year time scale and may therefore influence the temperature of the atmosphere (e.g. Berner, 1992). Thus, even to day, the weathering of basalt is an important factor in the net loss of CO_2 from the atmosphere, and it's general importance increases with geological age because the ratio of basalt to sedimentary rocks increases with the age of the crust (e.g. Ronov, 1964).

Iceland provides an opportunity to study the effects of the age of rocks, glaciation and vegetation on the nature and rate of chemical weathering of basalts. About 10% of the country is covered with glaciers, and one fourth is covered with vegetation. The interior of the country is unpopulated, providing pristine unpolluted catchment areas of uniform temperature and rock composition (basalt) with a variable glacier-and vegetation cover and variable runoff.

The objective of this paper is to define and interpret, the source of supply for the dissolved constituents in Icelandic rivers, the relative mobility of the elements during weathering of basalt, the rate of chemical denudation in Iceland and the effect of age of rocks, and glacier/ vegetation cover on the chemical weathering of basalt.

Results

Icelandic precipitation shows a normal distribution around a mean pH of 5.4. Na/Cl, K/Cl, Mg/ Cl, and Sr/Cl ratios in the precipitation are close to oceanic ratios, indicating a sole marine source for these elements in the precipitation. The concentration of Ca, SO_4, NO_3 and NH_3 is higher than predicted by an unfractionated marine contribution.

The pH of spring fed rivers in Iceland is high and they are relatively poor in total dissolved inorganic carbon, calcium and magnesium. The pH of other rivers ranges from 7.15 to 7.94, which is typical for waters with access to atmospheric CO_2 during or after water rock interaction. The silica concentration is lowest in rivers with high runoff in areas of old rocks but highest in geothermally contaminated rivers. The chlorine concentration is lowest in rivers with catchment areas furthest away from the coast and at the highest elevation, and the fluorine and phosphorus concentrations are higher in rivers draining young rocks than in those draining old rocks. The amount of total dissolved solids in Icelandic rivers is somewhat smaller than the world's average but their dissolved silica and sodium concentrations are greater. The concentration of major elements is at maximum in winter but reaches minimum in mid- and late summer when the river discharge is at maximum and a considerable part of the snow and ice melting on the glaciers, has been purified due to earlier partial melting of snow and ice. The water in the main channels of the rivers has long enough time for significant heat exchange with its surroundings and significant gas exchange with the atmosphere, but water rock interactions are insignificant.

The airborne dissolved or soluble solids contribution to the total dissolved solids in Icelandic rivers (only carbon dissolved in rain is considered), ranges from 14 % to 38% for those catchment areas that are closest to the coast. Most of the airborne contribution is of marine source and for the major elements in Icelandic river waters it is in descending order; Cl($\approx$100%) > Sr(44%) $\geqslant$ SO_4(42%) > Na(33%) > Mg(23%) $\geqslant$ K(21%) > Ca(13%) $\gg$ SiO_2(0%). Most of the nitrate and ammonia is airborne and the dissolved carbon in the Icelandic rivers is primarily, directly

or indirectly, derived from the atmosphere.

The average sequence of the relative mobility of elements during weathering of basalts in Iceland at present is SO_4 > F > Na > K $\gg$ Ca > SiO_2 > Mg > PO_4 > Sr $\gg$ Mn > Al > Fe > Ti. The sequence of the relative mobility of the elements varies from one catchment area to another. The relative mobility of Si, Mg, Ca and Sr increases with the age of the rocks and it increases for Ca and Sr with increased vegetation cover. The relative mobility of the least mobile elements during weathering in Iceland is similar to that found elsewhere in the world under remarkably variable climatic conditions.

The primary variables controlling the chemical denudation rate (t/km^2/y) in SW-Iceland are runoff and the age of rocks. The more the runoff and the younger the rocks, the greater the denudation rate. For most elements there is a gradual increase in the chemical denudation rate for rocks of the 'average age' 8 to 1 m.y. and then there is an abrupt increase for rocks younger than 1 m.y. Garrels and Mackenzie (1971) calculated the chemical denudation rates for the continents and found them to range from 2 t/km^2/y for Australia, to 42 t/km^2/y for Europe. Similar calculations yields 120 t/km^2/y for SW-Iceland. The calculated total chemical denudation rate of SW-Iceland, excluding bicarbonate is 55 t/km^2/y. Excluding bicarbonate is more compatible with the assessment of the chemical denudation rates of the various morphoclimatic types of the world by Meybeck (1979). The only morphoclimatic types that have higher chemical denudation rates than SW-Iceland are the mountainous regions of the humid temperate and humid tropical zones.

Summary and conclusions

Chemical weathering of primary minerals in Icelandic basalt is selective. The extent of selectivity depends on the weathering environment (Gíslason *et al.*, 1994). Vegetation cover decreases selective weathering of the primary minerals and therefore the difference in the relative mobility of the elements. With continuous vegetation cover the pH of the soil solutions tend to be low (< 7), glass, olivine, pyroxene and plagioclase are unstable, but the solutions are decreasingly saturated or more undersaturated with respect to zeolites, calcite and smectite, thus increasing the mobility of Ca and Mg. Since the weathering of Ca-Mg silicate rocks is the principal process whereby CO_2 is removed from the atmosphere on a geological time scale, the spread of vascular plants on the continents during the mid-Paleozoic , may have resulted in a drop in CO_2 (Berner 1993), not, necessarily because of greatly enhanced bulk chemical weathering, as suggested by Berner (1993), but rather due to the enhanced relative mobility of Ca and Mg.

Glacial cover slows down the overall chemical denudation rates in Iceland. It increases the probability of high pH weathering solutions by excluding direct and indirect routes for the CO_2 from the atmosphere to the weathering site, and by continuously exposing fresh rocks to the incoming solutions. High pH (8−10) makes the primary Ca-silicates stable and the Mg-silicates stable or less unstable and the high pH increases the probability of deposition of zeolites and smectites. Thus, the relative mobility of Ca and Mg, slows down under glacial cover, supporting the theory of negative feedback mechanism for the long term stabilization of the Earth's surface temperature (Walker *et al.*, 1981; Kump, 1989).

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