Factors controlling present weathering rates: new contributions from basalt erosion studies

P. Louvat
C. J. Allegre

Laboratoire de Géochimie et Cosmochimie, Institut de Physique du Globe de Paris, 4 place Jussieu, 75252 Paris Cedex 05, France

As chemical weathering of silicate rocks acts as a sink for atmospheric CO_2 and as greenhouse effect gases such as CO_2 have a leading role in climate regulation, much of river geochemical studies now focus on chemical and mechanical riverine erosion and on their controlling parameters. Moreover, weathering has probably had a dominating influence in the climatic evolution of the Earth, and studies of present weathering processes are likely to provide useful informations. First studies of present erosion have concerned the world-wide biggest drainage basins such as Congo and Amazon, but numerous other studies took an interest in smaller drainage basins with only one lithology or in a given type of climate. Among the existing studies of basalt erosion, the present ones have to their advantage to examine both chemical and mechanical weathering under various climatic and morphological settings.

Studies on four volcanic islands

Four volcanic islands were investigated: Réunion, Sao Miguel (Azores), Iceland and Java. River waters were sampled and analysed for their dissolved and suspended contents in order to determine their chemical and mechanical erosion rates. Chemical erosion rates were calculated after subtraction of rain and (possibly) geothermal spring inputs to the rivers. Mechanical erosion rates were estimated using the steady-state model of erosion, which assumes a mass budget between the chemical compositions of the initially unweathered rocks of the drainage basin and of the out-flowing dissolved and solid weathering products carried by the rivers. This steady-state approach has proved useful to provide mean mechanical erosion rates in cases where direct measurements of mechanical erosion are unsatisfactory or not available.

Variability of basalt erosion at the local scale of each island

On each island, in spite of everywhere-basaltic lithologies, chemical and mechanical erosion rates, but also chemical characteristics of the rivers are variable and many local small differences explain these variabilities. These differences concern the nature of the rocks (age, permeability, mineralogy, chemical composition) as well as the hydrologic and geographic settings (runoff, relief, vegetation, glaciers...).

On Réunion Island, chemical weathering in terms of total dissolved solids (TDS) is higher for the older volcanic massif than for the younger one, because of the longer retention time of the water in the older hydrologic system. Distinct chemical characteristics of the river waters are also recognized for these two Réunion volcanic massifs. In terms of total suspended solids (TSS), all rivers have similar concentrations but specific fluxes of suspended material are strongly correlated to runoffs.

On Sao Miguel (Azores), chemical characteristics of the river dissolved loads are clearly divided according to the differentiation index of the rocks (schematically basalts, trachytes and intermediate rocks). Nevertheless the resulting chemical weathering rates are not very different from one river to another and the differences among the mechanical erosion rates are rather related to geomorphological settings of the drainage basins than to the nature of the basaltic rocks.

In Iceland, water chemical compositions depend on the river hydrologic regime (glacial, spring-fed or direct-runoff rivers). The high mechanical weathering rates are due to the glaciers, which produce finely crushed material easily transportable by the rivers. Chemical weathering rates are conversely correlated to the age of the rocks.

On Java, the larger diversity of volcanic rocks compared to the three other islands (arc volcanism instead of hot spot volcanism) implies a large variability of the river chemical characteristics. Moreover, there is a clear distinction between the rivers draining plains and those draining mountain areas: chemical weathering is more efficient in plain rivers, whereas mountainous catchments have stronger mechanical erosion rates. Due to high population density, human activities undoubtedly influence the weathering processes.

Variability of basalt weathering at a global scale.

With these four studies, it is possible to examine one by one the parameters (temperature, runoff, relief, age of the rocks, vegetation...) that may influence weathering and explain the following distribution of the erosion rates. Chemical weathering rates are higher in Java than on Réunion and Sao Miguel islands and are even lower in Iceland. Rates of atmospheric CO_2 consumption by the chemical weathering are the highest for Java and Réunion and are lower for Sao Miguel and Iceland. Mechanical erosion rates are the highest in Iceland and Réunion, and are higher in Java than on Sao Miguel Island.

Temperature: The four islands offer the opportunity to cover a large range of water temperatures (5 to 30°C). We observe positive correlations between temperature, the rates of chemical erosion and of consumption of atmospheric CO_2, and the fluxes of many soluble elements. Such correlations can be explained by an Arrhenius law and the deduced activation energies give the following decreasing mobility sequence of the elements during basalt weathering: SiO_2> Na> Ca> Mg> K> Rb> Sr> Ba.

Runoff: The runoff variability is badly represented among our four studies (everywhere-oceanic climate with high precipitations), runoffs range between 500 and 7000 mm/yr. There is no obvious correlation between runoff and the weathering rates when these rates are expressed in terms of concentrations of dissolved and suspended material.

Topography: Catchment topography can be characterised by surface area, maximum altitude, length or slope. Again, maximum altitude variability is not well represented here, as it does not fall below 800 m for any of the drainage basins. Slope variability is larger, from 0.5 to 17%. Whereas chemical erosion rates seem to be insensitive to these morphological parameters, we observe positive correlation trends between surface areas, slopes of the drainage basins and mechanical erosion rates (and, by extension, the ratio of mechanical upon chemical erosion rates). Nevertheless, Java and Iceland must be considered as exceptions because of the Javanese plain-rivers and of the Icelandic glaciers.

Other parameters (vegetation, tectonic activity, climatic amplitude...) have an influence upon weathering processes but are difficult to characterise. The determination of the relative influence of each parameter is also hard to constrain, as all are intimately interlinked. Study of basaltic monolithologies has substantially reduced the complexity of weathering, but the variety of factors to consider remains too high for the major parameters to be picked out.

Relating chemical and mechanical erosions

For each river, we characterised the weathering state of the suspended material by comparing their soluble element concentrations to those of the drainage basin rocks: the more weathered the sediments, the larger the depletions of mobile elements. The comparison of these weathering states on the four studied islands lead us to consider the coupling between efficiency of the chemical weathering and efficiency of the transport. The weathering state of the suspended material transported by one river reflects a balance between the chemical and the mechanical erosion rates. In the case of Réunion Island, chemical erosion rates are very high but suspended sediments are very few weathered, because mechanical erosion rates are very high. In Java, in spite of chemical erosion rates comparable to those of Réunion, sediments are much more weathered because mechanical erosion rates are lower. For Sao Miguel rivers, relatively low chemical and mechanical erosion rates lead to rather weathered material. In Iceland, where chemical erosion rates are the lowest and mechanical erosion rates the highest, suspended sediments show a very low level of weathering.

Importance of basalt weathering in the global budgets of chemical and mechanical erosion

Once normalised to the drainage basin runoffs, the chemical and mechanical erosion rates we determined for the rivers of Réunion, Sao Miguel (Azores), Iceland and Java are very high in comparison with most of the world-wide largest rivers [(5)] and with the global means of silicate erosion rates. This is due to the basaltic lithology but also to the high runoffs, the high relief, the youthfulness and tectonic dynamic of these volcanic islands. Even if the individual river fluxes of dissolved and solid material to the ocean are negligible compared to large rivers, fluxes cumulated on the world-wide surface of the volcanic islands are no more negligible and should be taken into consideration in further estimations of global erosion rates.