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Short Communication: Aging of basalt volcanic systems and decreasing CO_2 consumption by weathering

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Abstract

Basalt weathering is one of many relevant processes balancing the global carbon cycle via land-ocean alkalinity fluxes. The CO_2 consumption by weathering can be calculated using alkalinity and is often scaled with runoff and/or temperature. Here it is tested if information on the surface age distribution of a volcanic system is a useful proxy for changes in alkalinity production with time.

A linear relationship between temperature normalized alkalinity fluxes and the Holocene area fraction of a volcanic field was identified, using information from 33 basalt volcanic fields, with an r^2=0.91. This relationship is interpreted as an aging function and suggests that fluxes from Holocene areas are ~10 times higher than those from old inactive volcanic fields. However, the cause for the decrease with time is probably a combination of effects, including a decrease in alkalinity production from surface near material in the critical zone as well as a decline in hydrothermal activity and magmatic CO_2 contribution.

A comparison with global models suggests, that global alkalinity fluxes considering Holocene active basalt areas are ~70% higher than the average from these models imply. The contribution of Holocene areas to the global basalt alkalinity fluxes is however only ~6%, because identified, mapped Holocene basalt areas cover only ~1% of the existing basalt areas. The large trap basalt proportion on the global basalt areas today reduces the relevance of the aging effect. However, the aging effect might be a relevant process during periods of globally, intensive volcanic activity, which remains to be tested.

1. Introduction

Basalt areas, despite its limited areal coverage, contribute significantly to the CO_2 sequestration by silicate rock weathering (Dessert et al., 2003; Gaillardet et al., 1999; Hartmann et al., 2009). The sensitivity of basalt weathering to climate change (Coogan and Dosso, 2015; Dessert et al., 2001; Dessert et al., 2003; Li et al., 2016) supports a negative weathering feedback in the carbon cycle that maintains the habitability of the Earth's surface over geological time scales (Berner, 1983; Li and Elderfield, 2013; Walker et al., 1981). Changes in volcanic weathering fluxes due to emplacement of large volcanic provinces or shifts in the geographic distribution of volcanic fields associated with continental drift may have contributed to climate change in the past (Goddéris et al., 2003; Kent and Muttoni, 2013; Schaller et al., 2012).

The role of basalt weathering in the carbon cycle and its feedback strength in the climate system depends, besides the release of geogenic nutrients, on the amount of associated CO_2 consumption and related alkalinity fluxes. The factors that module these fluxes are a subject to uncertainty. Previous studies suggest that basalt weathering contributes 25–35% to the global silicate CO_2 consumption by weathering (Dessert et al., 2003; Gaillardet et al., 1999; Hartmann et al., 2009). However, their estimations do not consider the potential aging of a weathering system. Young volcanic areas can show much higher weathering rates compared to older ones, as was shown for the Lesser Antilles, where a rapid decay of weathering rates within the first 0.5 Ma was observed (Rad et al., 2013). Such an aging effect of volcanic areas is difficult to parameterize for global basalt weathering fluxes, due to a lack of global compilations.

A practical approach to resolve this issue is to distinguish old and inactive volcanic fields (IVF) and active volcanic fields (AVF) (Li et al., 2016) and compare weathering fluxes with factors driving the weathering process, like land surface temperature or hydrological parameters. By compiling data from 37 basaltic fields globally, Li et al. (2016) showed that spatially explicit alkalinity fluxes (or CO_2 consumption rates) associated with basalt weathering correlate strongly with land surface temperature for IVFs, but not for AVFs. They suggested that previously observed correlations between weathering rates and runoff in global datasets originates partly from the coincidence of high weathering rates and high runoff of AVFs rather than a direct primary runoff control on the weathering rate. Many studied AVFs are located near the oceans and have an elevated topography, a combination, which can cause elevated runoff due to an orographic effect (Gaillardet et al., 2011). However, the here suggested aging effect on weathering rates from a volcanic system has not been evaluated.

The age distribution of the surface area of a whole volcanic system might be used as a first order proxy to study the variability of weathering fluxes of AVFs. However, the exact surface age of volcanic areas is rarely mapped in detail, but Holocene areas are often reported in geological maps. Here, basalt alkalinity fluxes are related to the calculated Holocene areal proportion of volcanic fields at the catchment scale. For this, the concept of weathering reactivity is introduced, which is the relative alkalinity flux of AVFs to the alkalinity flux estimated for IVFs by the function identified in Li et al. (2016). This reactivity R is compared with the relative age distribution of surface areas, using the fraction of the Holocene area on the total studied area. From this comparison a function for the decay of alkalinity fluxes with increasing proportion of older land surface area is derived and discussed.

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2. Methods

The volcanic fields used to establish the relationship between weathering reactivity and Holocene coverage are predominantly described as basalt areas (Li et al., 2016). Based on the availability of detailed geological maps 33 volcanic provinces were selected, with 19 IVFs and 14 AVFs. A detailed description is given in the supplementary information. The 14 AVFs are geographically widespread and diverse (Fig.1a). If the absolute age distribution of the volcanic rocks is available, the Holocene areas were mapped using the age range from 11.7 ka to present, according to the International Commission on Stratigraphy version 2017/02 (Cohen et al., 2013). If possible, coordinates of water sample locations were used to constrain catchment boundary to calculate the Holocene fraction for monitored areas. In some cases already existing alkalinity flux calculations were taken from Li et al. (2016). Detailed information on mapping and calculations for each system can be found in the supplementary information (SI).

The weathering reactivity (R) of each volcanic field is calculated by normalizing the observed alkalinity flux of the AVF ($F_{observed}$, in 10^6 mol km^{-2} a^{-1}) to that of the expected flux if the AVF would be an IVF ($F_{expected}$) applying the previously identified weathering function for IVFs (Li et al., 2016):

$$R = F_{observed}/F_{expected} \quad \text{(eq. 1)}$$

where the expected alkalinity flux $F_{expected}$ for IVFs is given by (Fig. 1b):

$$F_{expected}\ (10^6\ \text{mol km}^{-2}\ \text{a}^{-1}) = 0.2007 \times e^{(0.0692 \times T\ (°C))} \quad \text{(eq. 2)}$$

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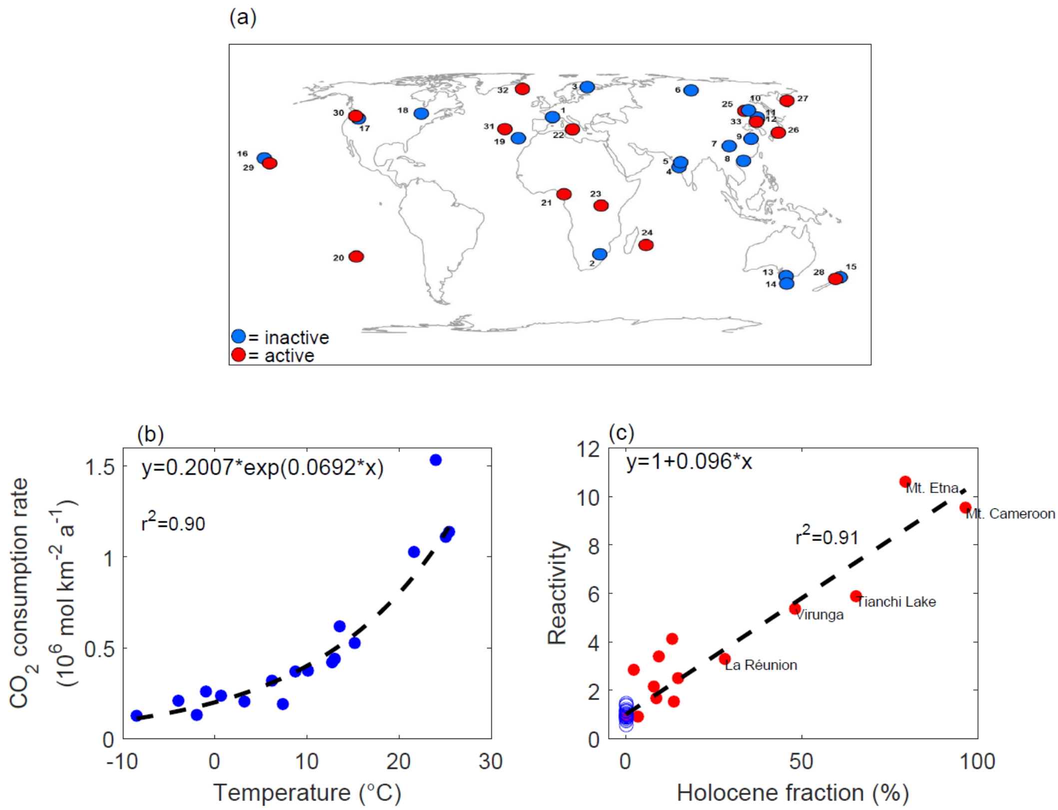

Figure 1. (a) The global map shows the locations of the Active Volcanic Fields (in red) and the Inactive Volcanic Fields (in blue) used in this study (1.Massif Central, 2.South Africa, 3.Karelia, 4.Coastal Deccan, 5.Interior Deccan, 6.Siberia Traps, 7.E'Mei, 8.Lei-Qiong, 9.Nanjing, 10.Xiaoxinganling, 11.Tumen River, 12.Mudan River, 13.SE Australia, 14.Tasmania, 15.North Island, NZ, 16.Kauai, Hawaii, 17.Columbia Plateau, 18.NE America, 19.Madeira Island, 20.Easter Island, 21.Mt.Cameroon, 22.Mt.Etna, 23.Virunga, 24.La Réunion, 25.Wudalianchi Lake, 26.Japan, 27.Kamchatka, 28.Taranaki, 29.Big Island, Hawaii, 30.High Cascades, 31.Sao Miguel, 32.Iceland, 33.Tianchi Lake). (b) The exponential relationship between alkalinity flux rates and the land surface temperature for IVFs (Li et al., 2016). (c) The relationship between the Holocene area fraction of a volcanic field and the weathering reactivity R (r^2=0.91).

IVFs range around a reactivity R=1 having a Holocene fraction of zero (Fig 1c). The reactivity R (eq. 1) of an AVF can be estimated by the Holocene area fraction as implied by the good linear correlation identified in Fig. 1c. The virtual reactivity for Holocene areas can be estimated rearranging eq. 1 and setting the area fraction to 100% :

$$F_{\mathrm{Holocene}} = R_{100\%\ Holocene} * F_{\mathrm{expected}} \qquad \text{(eq. 3)}$$

Global alkalinity fluxes from basalt areas are calculated using for older areas than of Holocene age equation 2 and for mapped Holocene areas equation 3. The model equations are calibrated for areas with a runoff > 74 mm a^{-1} to avoid too high alkalinity fluxes from drier areas with high temperature (*e.g.*, the Sahara Desert), assuming that neglecting fluxes from areas with lower runoff are not biasing the comparison (Tab. S1, supplementary information). In this case an overestimation is avoided.

Results are compared with four previous global empirical alkalinity flux models (Bluth and Kump, 1994; Dessert et al., 2003; Goll et al., 2014; Suchet and Probst, 1995). Alkalinity fluxes were translated into CO_2 consumption for allowing comparison with previous literature. For all models the same data input was used: a newly compiled global basalt map (mostly derived by the basalt lithological layer from the GLiM, but enhanced by mapped Holocene areas (SI; Hartmann and Moosdorf, 2012), additional regional geological maps reporting on basalt areas and the maps of the volcanic fields used in this study, for detailed information see supplementary information), temperature (Hijmans et al., 2005) and runoff (Fekete et al., 2002).

3. Results and Discussion

Studied IVFs are characterized by a Holocene volcanic surface area of 0% with weathering reactivity R ranging between 0.6 and 1.5 (Fig. 1c). In contrast, AVFs show a large range of Holocene coverage, from 0.2% (High Cascades) to 96.6% (Mount Cameroon), and weathering reactivity between 0.9 (Easter Island, High Cascades) and 10.6 (Mount Etna). The weathering reactivity correlates strongly with the percentage of Holocene area ($r^2 = 0.91$; Fig. 1c), suggesting Holocene surface area distribution to be a good predictor for the enhanced alkalinity fluxes from a volcanic system:

$$F_{alkalinity} = (1 + 0.096 \times H) \times 0.2007 \times e^{(0.0692 \times T)} \; [10^6 \text{ mol km}^{-2} \text{ a}^{-1}] \qquad \text{(eq. 4)}$$

where H is the Holocene fraction of a volcanic system in % and T is land surface temperature in °C.

The Holocene fraction is not interpreted as the physical cause for elevated alkalinity fluxes. Instead, magmatic CO_2 contribution, geothermal-hydrothermal activity and the input of new volcanic material to the surface (properties and “freshness” of the surface area for reaction) are contributing to enhanced alkalinity fluxes.

The magmatic CO_2 contributions to alkalinity fluxes in young volcanic systems may be large in general, but data are scarce to evaluate the global relevance for AVFs. For the Lesser Antilles a magmatic contribution of 23 to 40% to the CO_2 consumed by weathering was identified (Rivé et al., 2013). High ^{13}C-DIC values suggest that magmatic CO_2 contributes significantly to the alkalinity fluxes from the Virunga system (Balagizi et al., 2015). The magmatic CO_2 contribution derived from volcanic calcite dissolution on Iceland was estimated to be about 10% of the alkalinity fluxes for the studied area (Jacobson et al., 2015). In case of the Etna 7% of the CO_2 emitted due to volcanic activity may be captured by weathering (Aiuppa et al., 2000). These examples suggest that significant amounts of magmatic carbon may be transferred to the ocean directly via intra-volcanic weathering from AVFs.

The calculated global basalt weathering alkalinity fluxes based on previous global models (Bluth and Kump, 1994; Dessert et al., 2003; Goll et al., 2014; Suchet and Probst, 1995) give alkalinity fluxes ranging between 0.7 to 1.6 $\times 10^{12}$ mol a^{-1}. These values are different to previously published results based on the same models because a different geological map and climate data are used in this study. The new calculation based on the temperature dependence of weathering rate and the age dependence of weathering reactivity (eq. 4) results in higher global alkalinity fluxes of 2×10^{12} mol a^{-1} and 3.4 $\times 10^{12}$ mol a^{-1} for regions with > 74mm a^{-1} runoff, and for all areas, respectively. The latter higher estimate is mainly due to the modeled contribution from dry and hot regions and shows that it is relevant to apply the runoff cut off.

Using the new approach, considering the aging of a volcanic system, reveals that alkalinity fluxes from Holocene areas contribute only 6% to the global basalt weathering alkalinity flux. This is because identified mapped Holocene volcanic areas cover only ~1% of all basalt areas.

The Holocene area is probably underestimated due to information gaps in the reported age information of the global map. The strong dependence of weathering reactivity on relative age of the surface of a considered volcanic system suggests that it is relevant to know the global spatial age distribution of volcanic areas in more detail. Therefore, a new global review of the age distribution of basalt areas would be needed, which is beyond the scope of this study.

Table 1: Summary of CO_2 consumption rates for global basaltic areas applying different models and the new parameterization. For simplicity it was assumed that alkalinity fluxes equal CO_2 consumption.

		Global CO_2 consumption rate (10^9 mol/a) for limited area in comparison (only areas with > 74mm/a runoff)	Global CO_2 consumption rate (10^9 mol/a)
Dessert et al. 2003	runoff, temperature	1567	1573
Amiotte-Suchet & Probst, 1995	runoff	838	843
Bluth & Kump, 1994	runoff	739	754
Goll et al., 2014	runoff, temperature	1471	1477
New equation	temperature	1992	3431

The applied time stamp of the Holocene boundary suggests that the aging of the "weathering motor" of a basaltic volcanic area, including internal weathering, with declining volcanic activity is rather rapid. This implies that peaks in global volcanic activity have probably a short but intensive effect on the CO_2 consumption. A pronounced effect on the global carbon cycle by shifting the global reactivity of volcanic areas may only be relevant for geological periods with significantly elevated production of new volcanic areas, accompanied by geothermal-hydrothermal activity and capture of magmatic CO_2 before its escape to the atmosphere.

Results may have relevance for the carbon cycle and climate studies considering the displacement of large igneous provinces like the CAMP (Schaller et al., 2012) or the Deccan traps (Caldeira, 1990) with production of large basaltic areas within a short time. However, the biological contribution to CO_2 drawdown, via fertilization effects, *e.g.* P- or Si-release due to weathering and elevated CO_2 in the atmosphere must also be taken into account.

Looking deeper into Earth's history: variations in the solid Earth CO_2 degassing rate or changes in environmental conditions affecting the weathering intensity (Hartmann et al., 2017; Teitler et al., 2014) may have caused different reactivity patterns in dependence of surface age, if compared to the ones identified for the recent conditions.

In conclusion, a simple approach to detect an aging effect, using surface age as a proxy for several combined processes, was chosen due to availability of data. Nevertheless, the combined effect on elevated weathering reactivity due to magmatic CO_2 contribution, hydrothermal activity, production of fresh surface area for reaction, and hydrological factors of young volcanic systems remains to be disentangled, for single volcanic systems, as well as for the emplacement of larger, trap-style basalt areas.

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