



1 **Short Communication: Aging of basalt volcanic systems and decreasing CO₂ consumption**
2 **by weathering**

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9 **Abstract**

10 Basalt weathering is one of many relevant processes balancing the global carbon cycle via land-
11 ocean alkalinity fluxes. The CO₂ consumption by weathering can be calculated using alkalinity
12 and is often scaled with runoff and/or temperature. Here it is tested if information on the surface
13 age distribution of a volcanic system is a useful proxy for changes in alkalinity production with
14 time.

15 A linear relationship between temperature normalized alkalinity fluxes and the Holocene area
16 fraction of a volcanic field was identified, using information from 33 basalt volcanic fields, with
17 an $r^2=0.91$. This relationship is interpreted as an aging function and suggests that fluxes from
18 Holocene areas are ~10 times higher than those from old inactive volcanic fields. However, the
19 cause for the decrease with time is probably a combination of effects, including a decrease in
20 alkalinity production from surface near material in the critical zone as well as a decline in
21 hydrothermal activity and magmatic CO₂ contribution.

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

29 **1. Introduction**

30 Basalt areas, despite its limited areal coverage, contribute significantly to the CO₂ sequestration
31 by silicate rock weathering (Dessert et al., 2003; Gaillardet et al., 1999; Hartmann et al., 2009).
32 The sensitivity of basalt weathering to climate change (Coogan and Dosso, 2015; Dessert et al.,
33 2001; Dessert et al., 2003; Li et al., 2016) supports a negative weathering feedback in the carbon



34 cycle that maintains the habitability of the Earth's surface over geological time scales (Berner,
35 1983; Li and Elderfield, 2013; Walker et al., 1981). Changes in volcanic weathering fluxes due
36 to emplacement of large volcanic provinces or shifts in the geographic distribution of volcanic
37 fields associated with continental drift may have contributed to climate change in the past
38 (Goddéris et al., 2003; Kent and Muttoni, 2013; Schaller et al., 2012).

39 The role of basalt weathering in the carbon cycle and its feedback strength in the climate system
40 depends, besides the release of geogenic nutrients, on the amount of associated CO₂ consumption
41 and related alkalinity fluxes. The factors that modulate these fluxes are a subject to uncertainty.
42 Previous studies suggest that basalt weathering contributes 25–35% to the global silicate CO₂
43 consumption by weathering (Dessert et al., 2003; Gaillardet et al., 1999; Hartmann et al., 2009).
44 However, their estimations do not consider the potential aging of a weathering system. Young
45 volcanic areas can show much higher weathering rates compared to older ones, as was shown for
46 the Lesser Antilles, where a rapid decay of weathering rates within the first 0.5 Ma was observed
47 (Rad et al., 2013). Such an aging effect of volcanic areas is difficult to parameterize for global
48 basalt weathering fluxes, due to a lack of global compilations.

49 A practical approach to resolve this issue is to distinguish old and inactive volcanic fields (IVF)
50 and active volcanic fields (AVF) (Li et al., 2016) and compare weathering fluxes with factors
51 driving the weathering process, like land surface temperature or hydrological parameters. By
52 compiling data from 37 basaltic fields globally, Li et al. (2016) showed that spatially explicit
53 alkalinity fluxes (or CO₂ consumption rates) associated with basalt weathering correlate strongly
54 with land surface temperature for IVFs, but not for AVFs. They suggested that previously
55 observed correlations between weathering rates and runoff in global datasets originates partly
56 from the coincidence of high weathering rates and high runoff of AVFs rather than a direct
57 primary runoff control on the weathering rate. Many studied AVFs are located near the oceans
58 and have an elevated topography, a combination, which can cause elevated runoff due to an
59 orographic effect (Gaillardet et al., 2011). However, the here suggested aging effect on
60 weathering rates from a volcanic system has not been evaluated.

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

71



72 **2. Methods**

73 The volcanic fields used to establish the relationship between weathering reactivity and
74 Holocene coverage are predominantly described as basalt areas (Li et al., 2016). Based on the
75 availability of detailed geological maps 33 volcanic provinces were selected, with 19 IVFs and
76 14 AVFs. A detailed description is given in the supplementary information. The 14 AVFs are
77 geographically widespread and diverse (Fig.1a). If the absolute age distribution of the volcanic
78 rocks is available, the Holocene areas were mapped using the age range from 11.7 ka to present,
79 according to the International Commission on Stratigraphy version 2017/02 (Cohen et al., 2013).
80 If possible, coordinates of water sample locations were used to constrain catchment boundary to
81 calculate the Holocene fraction for monitored areas. In some cases already existing alkalinity
82 flux calculations were taken from Li et al. (2016). Detailed information on mapping and
83 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 $10^6 \text{ mol km}^{-2} \text{ a}^{-1}$) 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):

$$84 \quad R = F_{observed}/F_{expected} \quad (\text{eq. 1})$$

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

$$86 \quad F_{expected} (10^6 \text{ mol km}^{-2} \text{ a}^{-1}) = 0.2007 \times e^{(0.0692 \times T (^{\circ}\text{C}))} \quad (\text{eq. 2})$$

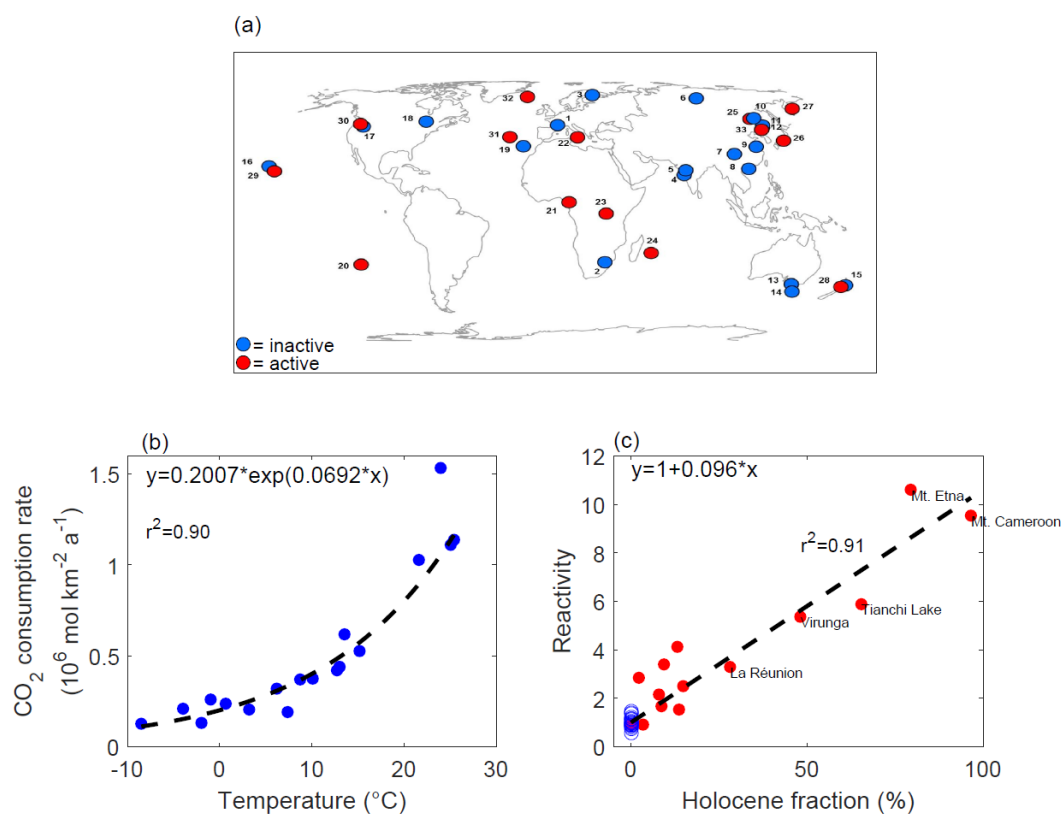


Figure 1. (a) The global map shows the locations of the Active Volcanic Fields (in red) and the Inactive Volcanic Fields (in blue) used in this study (1.Massif Central, 2.South Africa, 3.Karelia, 4.Coastal Deccan, 5.Interior Deccan, 6.Siberia Traps, 7.E'Mei, 8.Lei-Qiong, 9.Nanjing, 10.Xiaoxinganling, 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 ($r^2=0.91$).

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

$$91 \quad F_{\text{Holocene}} = R_{100\% \text{ Holocene}} * F_{\text{expected}} \quad (\text{eq. 3})$$



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

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

106

107 **3. Results and Discussion**

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

$$115 \quad F_{\text{alkalinity}} = (1 + 0.096 \times H) \times 0.2007 \times e^{(0.0692 \times T)} [10^6 \text{ mol km}^{-2} \text{ a}^{-1}] \quad (\text{eq. 4})$$

116 where H is the Holocene fraction of a volcanic system in % and T is land surface temperature in
117 $^{\circ}\text{C}$.

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

122 The magmatic CO_2 contributions to alkalinity fluxes in young volcanic systems may be large in
123 general, but data are scarce to evaluate the global relevance for AVFs. For the Lesser Antilles a
124 magmatic contribution of 23 to 40% to the CO_2 consumed by weathering was identified (Rivé et
125 al., 2013). High ^{13}C -DIC values suggest that magmatic CO_2 contributes significantly to the
126 alkalinity fluxes from the Virunga system (Balagizi et al., 2015). The magmatic CO_2 contribution



127 derived from volcanic calcite dissolution on Iceland was estimated to be about 10% of the
 128 alkalinity fluxes for the studied area (Jacobson et al., 2015). In case of the Etna 7% of the CO₂
 129 emitted due to volcanic activity may be captured by weathering (Aiuppa et al., 2000). These
 130 examples suggest that significant amounts of magmatic carbon may be transferred to the ocean
 131 directly via intra-volcanic weathering from AVFs.

132 The calculated global basalt weathering alkalinity fluxes based on previous global models (Bluth
 133 and Kump, 1994; Dessert et al., 2003; Goll et al., 2014; Suchet and Probst, 1995) give alkalinity
 134 fluxes ranging between 0.7 to 1.6 ×10¹² mol a⁻¹. These values are different to previously
 135 published results based on the same models because a different geological map and climate data
 136 are used in this study. The new calculation based on the temperature dependence of weathering
 137 rate and the age dependence of weathering reactivity (eq. 4) results in higher global alkalinity
 138 fluxes of 2×10¹² mol a⁻¹ and 3.4 ×10¹² mol a⁻¹ for regions with > 74mm a⁻¹ runoff, and for all
 139 areas, respectively. The latter higher estimate is mainly due to the modeled contribution from dry
 140 and hot regions and shows that it is relevant to apply the runoff cut off.

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

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

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Table 1: Summary of CO₂ consumption rates for global basaltic areas applying different models and the new parameterization. For simplicity it was assumed that alkalinity fluxes equal CO₂ consumption.

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		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

151



152 The applied time stamp of the Holocene boundary suggests that the aging of the “weathering
153 motor” of a basaltic volcanic area, including internal weathering, with declining volcanic activity
154 is rather rapid. This implies that peaks in global volcanic activity have probably a short but
155 intensive effect on the CO₂ consumption. A pronounced effect on the global carbon cycle by
156 shifting the global reactivity of volcanic areas may only be relevant for geological periods with
157 significantly elevated production of new volcanic areas, accompanied by geothermal-
158 hydrothermal activity and capture of magmatic CO₂ before its escape to the atmosphere.

159 Results may have relevance for the carbon cycle and climate studies considering the
160 displacement of large igneous provinces like the CAMP (Schaller et al., 2012) or the Deccan
161 traps (Caldeira, 1990) with production of large basaltic areas within a short time. However, the
162 biological contribution to CO₂ drawdown, via fertilization effects, *e.g.* P- or Si-release due to
163 weathering and elevated CO₂ in the atmosphere must also be taken into account.

164 Looking deeper into Earth’s history: variations in the solid Earth CO₂ degassing rate or changes
165 in environmental conditions affecting the weathering intensity (Hartmann et al., 2017; Teitler et
166 al., 2014) may have caused different reactivity patterns in dependence of surface age, if
167 compared to the ones identified for the recent conditions.

168 In conclusion, a simple approach to detect an aging effect, using surface age as a proxy for
169 several combined processes, was chosen due to availability of data. Nevertheless, the combined
170 effect on elevated weathering reactivity due to magmatic CO₂ contribution, hydrothermal
171 activity, production of fresh surface area for reaction, and hydrological factors of young volcanic
172 systems remains to be disentangled, for single volcanic systems, as well as for the emplacement
173 of larger, trap-style basalt areas.

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