Mayotte Critical Zone Observatory: Preliminary Results on Chemical Weathering and Erosion Rates on Volcanic Edifices

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Available online at www.sciencedirect.com
ScienceDirect
Procedia Earth and Planetary Science 10 (2014) 73 – 76
Procedia
Earth and Planetary Science

Geochemistry of the Earth's Surface meeting, GES-10

Mayotte Critical Zone Observatory: preliminary results on chemical weathering and erosion rates on volcanic edifices

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Abstract

This is the first multidisciplinary study on the critical zone of the French volcanic island of Mayotte to address chemical weathering rates. Here we present the first estimation of chemical weathering rates using element fluxes transported in surface and subsurface waters, ranging from 49 to 306 t/km²/yr for rivers and 113 to 1,382 t/km²/yr for groundwater. These results are consistent with the weathering pattern of other tropical volcanic islands and support the hypothesis that subsurface waters transport more solutes to the ocean than surface waters. In addition, a helicopter-borne resistivity survey was correlated to borehole geological data to understand the hydrogeological functioning of the "deep critical zone".

Peer-review under responsibility of the Scientific Committee of GES-10

Keywords: Mayotte, chemical weathering, erosion, volcanic island, hydrogeological budget, airborne geophysics

1. Introduction

Chemical weathering and mechanical erosion are the two processes that modify the critical zone (CZ). Among silicate rocks it is now well established that basalts have some of the highest rates [1-5]. Erosion rates on volcanic islands in particular are locally more than three orders of magnitude higher than the global average ([2, 5]). Hydrological balance studies on tropical volcanic islands have recently shown that subsurface water fluxes may contribute to a greater extent than rivers to the chemical weathering budget [3, 6]. This led to a renewed focus on the

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Peer-review under responsibility of the Scientific Committee of GES-10
doi:10.1016/j.proeps.2014.08.014

processes and parameters that control weathering and erosion fluxes on large scales, such as lithology, climate, topography, hydrology, land use, and hydrothermal contributions.

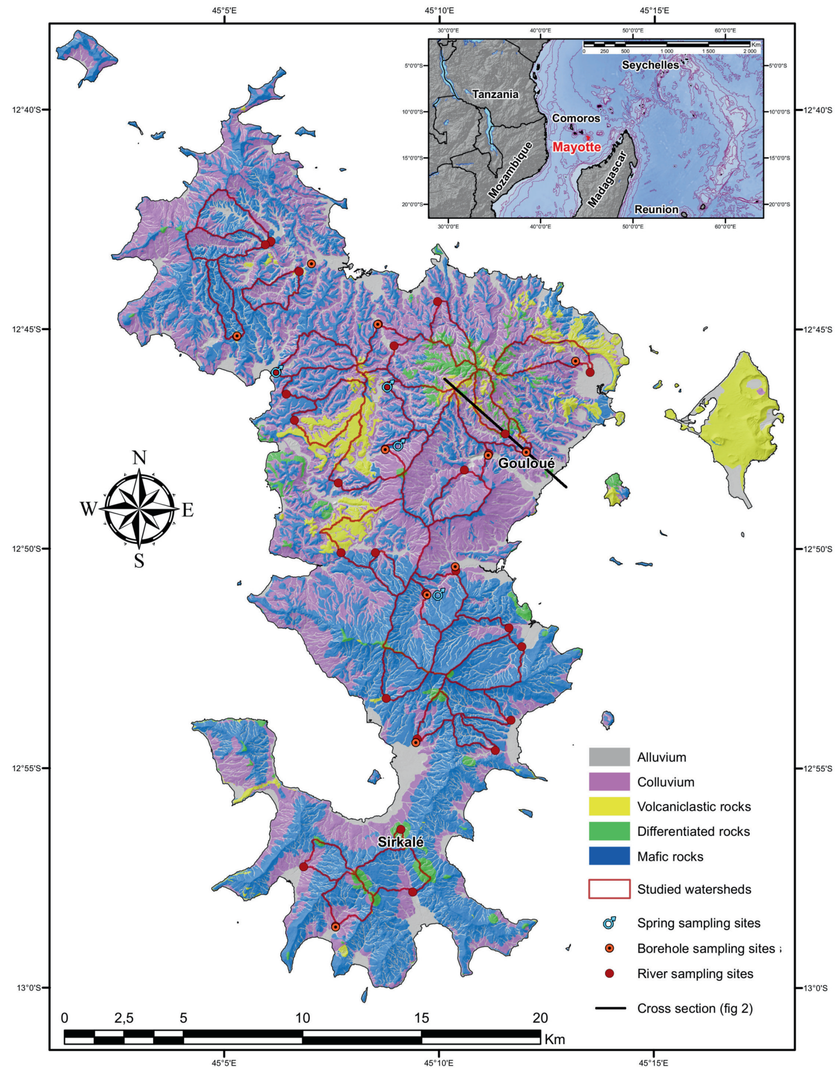

Figure 1: Simplified geological map of Mayotte based on [7], with sampling locations (February 2013 campaign).

The island of Mayotte extends over a 374 km² area, culminates at 660 m, has a highly indented coastline, and is surrounded by a large barrier reef and lagoon. It has a tropical climate with high temperatures (23°C-30°C), high precipitation (1,400 mm/yr subject to a monsoon regime), dense tropical vegetation and steep slopes. The onshore volcanic activity history dates from 7 ka to 10 Ma, consisting of basaltic lava, phonolitic massifs and pyroclastic deposits [8], with an extensive lateritic formation covering more than 70% of the island [9]. The hydrogeological model (based on a combined airborne geophysics and hydrogeology approach) shows a 'fragmented' character resulting from several phases of volcanic construction and erosion over the last 10 Ma [10].

This paper presents the first quantification of chemical weathering and erosion rates on the volcanic island of Mayotte through a multidisciplinary approach (CZ Observatory of Mayotte, **http://www.czen.org/content/czo-mayotte**) with (1) the chemical weathering budgets for both surface and subsurface waters, and (2) the digital elevation model (DEM) based erosion rate calculations.

2. Materials and methods

We conducted two field campaigns in 2013 (February and July). Only the wet season data (February) is presented here. Water was sampled from watersheds and shallow wells over the whole island. Cation and trace element concentrations were determined by ICP-MS and anion concentrations by ionic chromatography and molecular absorption spectrometry. Chemical weathering rates were deduced from the corrected TDS (from atmospheric inputs) and terms of the hydrological budget (surface runoff, subsurface infiltration).

The erosion rate calculation was focused on 11 valleys located around the most recent major volcanoes of the island (Digo and M'Tsapéré; 0.9 – 0.75 Ma), where paleosurfaces are well preserved. Absolute dating obtained from ref. [8], have been extrapolated to these surfaces on the basis of paleomagnetic data, morphological data and field knowledge. Old paleosurfaces were extrapolated from preserved remnants on the crests. The eroded volume was deduced on the basis of the difference from the current topographical surface. A 5 m resolution lidar acquired DEM was used with ESRI ArcGIS 10 software.

3. Chemical weathering rates

3.1. Hydrological & weathering budget

The total dissolved solid (TDS) load ranged from 71 to 538 mg/l (mean 209 mg/l) for rivers (surface) and from 92 to 971 mg/l (mean 370 mg/l) for subsurface waters. In February, the amount of runoff was 16 to 25% of the incident rainfall, while infiltration reached 27 to 49%. Calculated weathering rates ranged from 49 to 306 t/km²/yr (mean 119 t/km²/yr) for rivers and from 113 to 1,382 t/km²/yr (mean 462 t/km²/yr) for subsurface water fluxes. For surface waters, the highest rate was noted for Sirkalé river (figure 1), which has a hydrochemical signature rich in major and trace elements tracing hydrothermalism impact. According to these high weathering rates, Mayotte has a weathering pattern resembling that of other volcanic islands [4]. However, the dominant contribution from groundwaters support the hypothesis that surface water, in comparison to the subsurface water, may have a minor role in transporting dissolved material into oceans [3, 4]. This high contribution from subsurface water likely results from a combination of high infiltration rates, high water-rock interaction surfaces, as well as localized hydrothermally altered rocks. These different processes may also be assessed via geophysical data. We present an example of the "Gouloué" area in which we calculated a 7-fold higher weathering rate for subsurface water fluxes than for rivers.

3.2. The Gouloué example

The studied watershed area is 5.43 km². Its outcropping geology shows 39% phonolites, 36% volcaniclastic rocks and 25% basaltic rocks. There are three recent boreholes (F1, F2, F3, figure 2) in which water presented increasing conductivity (460, 485 & 612 µS/cm, respectively). The 'Gouloué' sample (figure 1) was taken in the F3 borehole, which was more than 90 m deep. The main water supply was 45-46 m deep, within a sub-aphyric vacuolar basalt [11]. The water had very high TDS (502 mg/l) and was accompanied by a high weathering rate of 791 t/km²/yr.

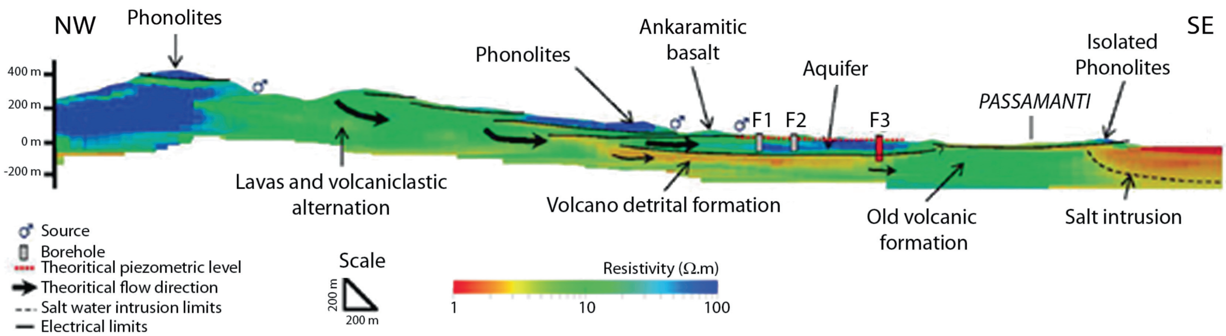

Figure 2: TDEM data crosssection of Gouloué valley. Localization figure 1.

The lithological interpretation of the resistivity (phonolites (> 100 Ω.m), alternation of massive lava (50 to 140 Ω.m), volcano-detritic & inter-stratified formations (2-10 to 50 Ω.m)) allowed characterization of the paleovalley geometry. The substratum of old and potentially weathered lava was filled by a younger lava flow within which groundwater circulates [10]. Monitoring the confined aquifer over a long distance implied a substantial temporal interaction with the host rock, as confirmed by the evolution of conductivity in the boreholes. In addition, although there was no evidence of hydrothermal activity locally at drilling sites, the upstream recharge area (not precisely located) was surrounded by many phonolites associated with hydrothermal weathering aureoles [9].

4. Erosion rates

The calculated erosion rates ranged from 10 to 86 $m^3/km^2/yr$. These results will soon be improved by calculating the uncertainties related to the spatial statistics, but they are already very close to those obtained by Ferrier et al. [5] on the old Hawaiian island of Kaua'i (2 to 80 $m^3/km^2/yr$ for small watersheds). Erosion on Digo, 10 to 42 (mean 20) $m^3/km^2/yr$, was 2.6-fold lower than that of M'Tsapéré, 40 to 86 (mean 52) $m^3/km^2/yr$.

As the rainfall and runoff of the two studied volcanoes (Digo and M'Tsapéré) were very similar, the erosion rate distribution appeared to be the result of the interaction of several factors, such as morphology, lithology or prevailing winds. Digo is lower (255 m), with softer and more sheltered slopes than M'Tsapéré (572 m), which also has greater lithological variability.

5. Conclusion

This study provided a first quantification of chemical weathering rates (49 to 306 $t/km^2/yr$ for rivers and 113 to 1,382 $t/km^2/yr$ for subsurface waters), and erosion rates (10 to 86 $m^3/km^2/yr$) in Mayotte. These results are similar to those obtained on other volcanic islands, and highlight the marked contribution of subsurface water fluxes to the weathering budget. The next step of this multidisciplinary study on the critical zone of Mayotte will concern the coupling of the petrology and the geochemistry of the weathering profiles with high-resolution geophysics.

Acknowledgements

We thank the BRGM Research Division & DEAL for financial support, and Mayotte's BRGM team for their helpful field support. We thank Karine Rivé for helpful discussions on weathering processes on volcanic islands. We thank David Manley for English corrections and Kate Maher for helpful review.

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