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Volcanic Lakes in Africa: The VOLADA_Africa 2.0 Database, and Implications for Volcanic Hazard

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Volcanic lakes pose specific hazards inherent to the presence of water: phreatic and phreatomagmatic eruptions, lahars, limnic gas bursts and dispersion of brines in the hydrological network. Here we introduce the updated, interactive and open-access database for African volcanic lakes, country by country. The previous database VOLADA (VOlcanic LAke DAta Base, Rouwet et al., Journal of Volcanology and Geothermal Research, 2014, 272, 78–97) reported 96 volcanic lakes for Africa. This number is now revised and established at 220, converting VOLADA_Africa 2.0 in the most comprehensive resource for African volcanic lakes: 81 in Uganda, 37 in Kenya, 33 in Cameroon, 28 in Madagascar, 19 in Ethiopia, 6 in Tanzania, 2 in Rwanda, 2 in Sudan, 2 in D.R. Congo, 1 in Libya, and 9 on the minor islands around Africa. We present the current state-of-the-art of arguably all the African volcanic lakes that the global experts and regional research teams are aware of, and provide hints for future research directions, with a special focus on the volcanic hazard assessment. All lakes in the updated database are classified for their genetic origin and their physical and chemical characteristics, and level of study. The predominant rift-related volcanism in Africa favors basaltic eruptive products, leading to volcanoes with highly permeable edifices, and hence less-developed hydrothermal systems. Basal aquifers accumulate under large volcanoes and in rift depressions providing a potential scenario for phreatomagmatic volcanism. This hypothesis, based on a morphometric analysis and volcanological research from literature, conveys the predominance of maar lakes in large monogenetic fields in Africa (e.g. Uganda, Cameroon, Ethiopia), and the absence of peak-activity crater lakes, generally found at polygenetic arc-volcanoes. Considering the large number of maar lakes in Africa (172), within similar geotectonic settings and meteoric conditions as in Cameroon, it is somewhat surprising that “only” from Lake Monoun and Lake Nyos fatal CO_2 bursts have been recorded. Explaining why other maars did *not* experience limnic gas bursts is a question that can only be answered by enhancing insights into physical limnology and fluid geochemistry of the so far poorly studied lakes. From a hazard perspective, there is an urgent need to tackle this task as a community.

Keywords: Africa, volcanic lakes, maar, Lake Nyos, database, hazard assessment

INTRODUCTION

The Cameroonian "killer lakes" Nyos and Monoun (Western Africa, **Figure 1**) are reputable for having induced the boom in volcanic lake studies since the late 1980s (e.g. Kling et al., 1989; Giggenbach, 1990; Giggenbach et al., 1991; Freeth, 1992; Evans et al., 1993, 1994; Freeth, 1994; Martini et al., 1994; Zhang, 1996, 1998; Viollier et al., 1995, 1997; Aeschbach-Hertig et al., 1996, 1999), to such a degree to have introduced a "Nyos bias" – for the good and the bad – on how to cope with lakes in volcanic craters in terms of hazard assessment and risk mitigation strategies (Rouwet et al., 2015a, 2019; Rouwet, 2021). A major question that arose from most of these Nyos-biased studies was whether any other lakes were capable of bursting CO_2 in a sudden manner as Lakes Monoun and Nyos did in 1984 and 1986, respectively. Despite three decades of post-Nyos research, this question still remains unanswered for too many lakes (Rouwet, 2021).

The Nyos bias expresses an ambiguity. On the one hand, dynamics at other lakes, in Africa and other continents, are often over-interpreted as if they should be Nyos-type lakes (i.e. volcanic lakes affected by cyclical, explosive gas release due to gas pressure build up in deep waters) when CO_2 degassing occurs in those lake areas; this view might be most prudent, in case of doubt, although it turns out to be unrealistic in some cases (e.g. Rouwet et al., 2019). On the other hand, the only way to discover whether CO_2, or other gas species, are accumulated up to critical pressure conditions in deep lake strata is to lower Conductivity-Temperature-Depth/Pressure (CTD) probes, sample lake water and measure dissolved gases along vertical profiles. This direct investigation has been applied only to a few lakes in order to have a complete picture of how volcanic lake degassing works. Nevertheless, it is a fact that, especially, the 1986 Lake Nyos gas burst has increased the general awareness of the potential danger this type of volcanic lakes poses (e.g. Giggenbach et al., 1991; Martini et al., 1994; Aeschbach-Hertig et al., 1996, 1999; Caliro et al., 2008; Carapezza et al., 2008; Chiodini et al., 2012; Cabassi et al., 2013, 2014; Rouwet et al., 2019, 2020; Rouwet, 2021).

Rouwet et al. (2014) introduced the first, incomplete version of the community-based, interactive, and open-source (https://vhub.org/resources/2437) VOlcanic LAkes DAta base (VOLADA). Out of respect for Lake Nyos, "the mother of volcanic lakes," here we first provide an update on the post-Pliocene (i.e. contemporaneous) volcanic lakes located on the African continent, Madagascar and minor islands (Annobon, Bioko, Tristan da Cunha, Karthala, Mohéli Island and Mayotte, **Figure 1**), presented as VOLADA_Africa 2.0. This version aims to *1*) supply an updated list of the geo-referenced volcanic lakes, *2*) shed light on the type of each lake, following classical (Pasternack and Varekamp, 1997; Varekamp et al., 2000) and novel (Christenson et al., 2015) classification schemes, *3*) show a realistic picture on the level of study of each volcanic lake in Africa, regarding volcanological research *sensu lato*, and *4*) provide a hazard assessment related to volcanic lakes in Africa. As volcanological literature revealed the maar nature of many of the catalogued lakes, an analysis of morphometric parameters for maar *craters* (Graettinger, 2018) for the entire database leads to a conceptual model that corroborates why African volcanic lakes actually are predominantly maar lakes. Consequently, we suggest strategies for future research and monitoring setups for those lakes we deem as potentially hazardous, or as peculiar for other reasons from a volcanological point of view.

THE VOLCANIC LAKE CATALOGUE FOR AFRICA

VOLADA "1.0"

VOLADA was introduced by Rouwet et al. (2014) with the aim to review and update the number of volcanic lakes reported in earlier studies (e.g. Delmelle and Bernard, 2000; Pérez et al., 2011; Lockwood and Kusakabe, 2018) and to better locate them on the globe. VOLADA aimed at being an interactive and open-access tool, perennially open for discussion, additions and corrections by the entire scientific community. In 2014, VOLADA listed 474 volcanic lakes, with 86 lakes in Europe (30 in the Azores), 97 in Africa (20 in Cameroon), 51 in North America (21 in Mexico), 58 in Central America (27 in Costa Rica), 28 in South America (18 in Chile-Argentina), 111 in Asia (33 in Indonesia), and 43 in Oceania (27 in New Zealand). If sufficient information was available, the lakes were classified following the physical (a scale from 1 to 10, based on the state of activity of the hosting volcano; Pasternack and Varekamp, 1997), and chemical properties of the lake water ("gas-dominated" versus "rock-dominated" lake waters, G versus R, Varekamp et al., 2000). The level of study of each lake was reported as a numerical scale from 1 to 5, from "well studied" (1) to "poorly or not studied" (5).

VOLADA_Africa 2.0: Revised Methodology

Subsequently, Christenson et al. (2015) proposed (by KN) an alternative classification scheme, based on the genetic process behind the lake basin formation, regardless of the current state of activity of the lakes, or the chemical-physical properties of the lake water. The latter information appeared to be often unavailable, as a consequence of the general poor level of study of most lakes.

The genetic classification scheme by Christenson et al. (2015) follows some basic rules, and results in alphanumerical codes (G0-1_R0-1_T0-1_L0-1), as:

(1) The ***geotectonic assessment*** in which the lake is located (G) can be related to monogenetic (0), or polygenetic (1) volcanism;
(2) The ***relationship*** between the volcanism and the eventual lake formation (R) is weak (0), or strong (1);
(3) The ***timing of lake formation*** in relation with the volcanism (T) can be long (0) or shortly (1) after the volcanic activity;
(4) The ***location*** of the volcanic lake in relation to the volcanic centre (L) can be off (0) or over (1) the vent.

A major accomplishment of this genetic classification scheme is to eliminate the ambiguity that existed in naming "volcanic lakes," as each alphanumerical code points to a specific type of

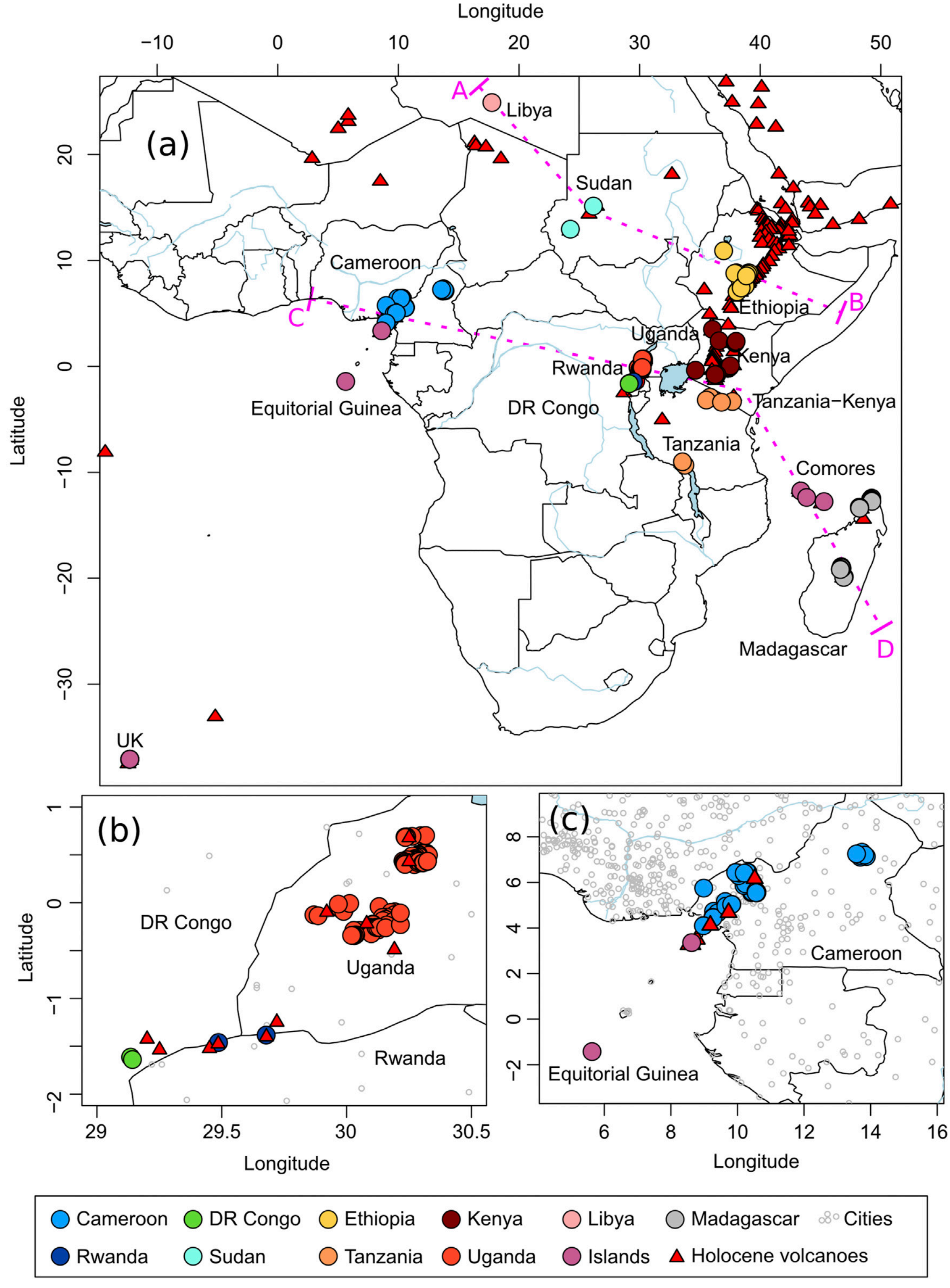

FIGURE 1 | (A) Location map of the African volcanic lakes, color-coded per country. The zoomed area mainly shows the lakes in Bunyaruguru, Ndali-Kasenda and Fort Portal volcanic fields in Uganda **(B)**, and the Cameroon Volcanic Line **(C)**. Holocene active volcanoes are exported from the Global Volcanism Program-Smithsonian database (https://volcano.si.edu/).

TABLE 1 | The VOLADA_Africa 2.0 database, mentioning the lake number (#), the number of lakes in the same country (#/country), the lake name, the volcano the depends on, the country, GVP number (Global Volcanism Program number https://volcano.si.edu/search_volcano.cfm), volcano type, the latitude and longitude (Lat. and Long. in decimal coordinates), the elevation above sea level (m a.s.l.), level of study (1–5, *see* text for details), genetic class (*see* text for details), lake type, physical and chemical classification, length of major and minor lake axes (Dmajor and Dminor, respectively, in m), lake surface area (A, in m^2), lake perimeter (in meter), Aspect Ratio (AR, **Eq. 1**), Elongation (EL, **Eq. 2**), Isoperimetric Circularity (IC, **Eq. 3**).

#	#/Country	Lake	Volcano	Country	GVP number	Volcano type	Lat.	Long.	Elevation (m asl)	Level of study	Genetic class	Lake type	Phys. Class	Chem. Class	D major (m)	D minor (m)	A (m^2)	Perimeter (m)	AR	EL	IC
1	1	Baleng	Oku volcanic field	Cameroon	224030	stratovolcano	5.550199	10.420998	1,390	3	G0R1T1L1	maar	6	R	390	245	7.87E+04	1,120	0.628	0.659	0.788
2	2	Banefo	Oku volcanic field	Cameroon	224030	stratovolcano	5.586977	10.442195	1,116	3	G0R1T1L1	maar	6	R	380	175	4.79E+04	960	0.461	0.422	0.653
3	3	Bambuluwe	Oku volcanic field	Cameroon	224030	stratovolcano	5.861728	10.197675	2,088	3	G0R1T1L1	maar	6	R	530	445	1.82E+05	1,630	0.840	0.825	0.861
4	4	Bambili	Oku volcanic field	Cameroon	224030	stratovolcano	5.935203	10.243734	2,268	3	G0R1T1L1	maar	6	R	590	325	1.78E+05	1,615	0.551	0.651	0.858
5	5	Benakuma	Oku volcanic field	Cameroon	224030	stratovolcano	6.431842	9.945516	604	3	G0R1T1L1	maar	6	R	1,590	1,365	1.60E+06	5,900	0.858	0.806	0.578
5	5	Elum	Oku volcanic field	Cameroon	224030	stratovolcano	6.339768	10.036545	968	3	G0R1T1L1	maar	6	R	635	600	2.66E+05	1,885	0.945	0.840	0.941
6	6	Enep/Nfou	Oku volcanic field	Cameroon	224030	stratovolcano	6.298281	10.036264	725	3	G0R1T1L1	maar	6	R	690	510	2.99E+05	2,195	0.739	0.800	0.780
7	7	Mfouet	Oku volcanic field	Cameroon	224030	stratovolcano	5.537339	10.57993	1,076	3	G0R1T1L1	maar	6	R	345	275	5.76E+04	1,110	0.797	0.616	0.587
8	8	Monoun	Oku volcanic field	Cameroon	224030	stratovolcano	5.579649	10.586533	1,081	1	G0R1T1L1	maar	5b2	R	1,280	215	5.96E+05	5,545	0.168	0.463	0.244
9	9	Nchout	Oku volcanic field	Cameroon	224030	stratovolcano	5.612168	10.556276	1,095	3	G0R1T1L1	maar	6	R	615	435	1.60E+05	2,005	0.707	0.539	0.500
10	10	Nyi	Oku volcanic field	Cameroon	224030	stratovolcano	6.445293	10.314747	1,026	3	G0R1T1L1	maar	6	R	665	220	1.64E+05	2,380	0.331	0.472	0.364
11	11	Nyos	Oku volcanic field	Cameroon	224030	stratovolcano	6.439224	10.298051	1,103	1	G0R1T1L1	maar	5b2	R	1,655	1,005	1.56E+06	6,565	0.607	0.725	0.455
12	12	Negop Baghang	Oku volcanic field	Cameroon	224030	stratovolcano	5.545605	10.560219	1,098	3	G0R1T1L1	maar	6	R	330	225	5.93E+04	995	0.682	0.693	0.753
13	13	Oku	Oku volcanic field	Cameroon	224030	stratovolcano	6.189813	10.452087	2,239	3	G0R1T1L1	maar	6	R	2,010	1,285	2.26E+06	6,075	0.639	0.713	0.771
14	14	Kuk	Oku volcanic field	Cameroon	224030	stratovolcano	6.408605	10.205016	1,325	3	G0R1T1L1	maar	6	R	810	625	3.90E+05	2,425	0.772	0.757	0.833
15	15	Wum	Oku volcanic field	Cameroon	224030	stratovolcano	6.407756	10.055327	1,081	3	G0R1T1L1	maar	6	R	755	595	3.14E+05	2,310	0.788	0.701	0.739
16	16	Dissoni	Tombel Graben	Cameroon	224011	pyroclastic cones	4.730564	9.282076	462	3	G0R1T1L1	maar	6	R	1,480	1,395	1.51E+06	5,195	0.943	0.878	0.703
17	17	Barombi Mbo	Tombel Graben	Cameroon	224011	pyroclastic cones	4.660476	9.40197	314	2	G0R1T1L1	maar	6	R	2,560	2,250	4.09E+06	7,775	0.879	0.795	0.850
18	18	Barombi Koto	Tombel Graben	Cameroon	224011	pyroclastic cones	4.468989	9.259588	102	3	G0R1T1L1	maar	6	R	1,470	1,140	1.23E+06	5,110	0.776	0.725	0.592
19	19	Mboandong	Tombel Graben	Cameroon	nd	nd	4.450808	9.268923	150	3	G0R1T1L1	maar	6	R	535	440	1.53E+05	1,555	0.822	0.681	0.795
20	20	Beme	Cameroon volcanic line	Cameroon	nd	nd	5.158609	9.634794	473	3	G0R1T1L1	maar	6	R	670	610	3.35E+05	2,315	0.910	0.950	0.785
21	21	Ejagham/Idjagham	Cameroon volcanic line	Cameroon	nd	nd	5.749801	8.986962	141	3	G0R1T1L1	maar	6	R	1,015	715	5.15E+05	2,960	0.704	0.636	0.739
22	22	Edib	Cameroon volcanic line	Cameroon	nd	nd	4.957423	9.65178	1,269	3	G0R1T1L1	maar	6	R	510	430	1.85E+05	1,560	0.843	0.906	0.955
23	23	Manengouba-F	Mt Manengouba	Cameroon	nd	stratovolcano	5.035733	9.831024	1,914	3	G1R1T1L1	crater	6	R	735	620	3.62E+05	2,610	0.844	0.853	0.668
24	24	Manengouba-M	Mt Manengouba	Cameroon	nd	stratovolcano	5.032399	9.826107	1,932	3	G1R1T1L1	crater	6	R	260	175	3.40E+04	840	0.673	0.640	0.606
25	25	Debundsha Big	Mt Cameroon	Cameroon	224010	stratovolcano	4.104048	8.980358	64	3	G1R1T1L0	maar	6	R	335	255	7.29E+04	1,140	0.761	0.827	0.705
26	26	Debundsha Small	Mt Cameroon	Cameroon	224010	stratovolcano	4.09697	8.979062	32	3	G1R1T1L0	maar	6	R	80	55	2.00E+00	250	0.688	0.000	0.000
27	27	Baledjam Marbuwi	Volcanic plateau of Adamawa	Cameroon	nd	nd	7.13493	13.870481	1,256	3	G0R1T1L1	maar	6	R	575	510	1.86E+05	1,760	0.887	0.716	0.755
28	28	Ngaoundaba	Volcanic plateau of Adamawa	Cameroon	nd	nd	7.130619	13.693898	1,163	3	G0R1T1L1	maar	6	R	495	200	8.62E+04	1,820	0.404	0.448	0.327
29	29	Gegouba	Volcanic plateau of Adamawa	Cameroon	nd	nd	7.108046	13.689856	1,182	3	G0R1T1L1	maar	6	R	415	395	1.20E+05	1,450	0.952	0.887	0.717
30	30	unnamed	Volcanic plateau of Adamawa	Cameroon	nd	nd	7.181089	13.689974	1,200	3	G0R1T1L1	maar	6	R	390	275	8.73E+04	1,165	0.705	0.731	0.808
31	31	Mbalang	Volcanic plateau of Adamawa	Cameroon	nd	nd	7.324499	13.738696	1,105	3	G0R1T1L1	maar	6	R	1,065	485	4.18E+05	2,785	0.455	0.469	0.677
32	32	Fonjak	Volcanic plateau of Adamawa	Cameroon	nd	nd	7.198734	13.825379	1,072	3	G0R1T1L1	maar	6	R	595	490	2.60E+05	1,980	0.824	0.934	0.833
33	33	Tisong	Volcanic plateau of Adamawa	Cameroon	nd	nd	7.253456	13.577037	1,152	3	G0R1T1L1	maar	6	R	305	210	6.25E+04	1,060	0.689	0.855	0.699
34	1	Lac Vert	between Nyiragongo and Lake Kivu	DR Congo	nd	tuff cone	−1.613553	29.135044	1,471	4	G0R1T1L1	tuff cone	6	R	680	340	1.93E+05	1,805	0.500	0.531	0.744
35	2	Kirunga	between Nyiragongo and Lake Kivu	DR Congo	nd	tuff cone	−1.638970	29.142168	1,470	4	G0R1T1L2	tuff cone	6	R	160	95	1.09E+04	415	0.594	0.544	0.798
36	1	Ara Shetan	Butajiri Silti Field	Ethiopia	221260	fissure vents	8.044047	38.351203	2,041	5	G0R1T1L1	maar	6	R	510	460	1.82E+05	1,620	0.902	0.891	0.871
37	2	Budameda	Bilate River Field	Ethiopia	221291	monogenetic volcanic field	7.09532	38.091476	1,555	5	G0R1T1L1	maar	6	R	1,280	1,010	1.02E+06	3,750	0.789	0.793	0.911
38	3	Tilo	Bilate River Field	Ethiopia	221291	monogenetic volcanic field	7.063846	38.095431	1,555	5	G0R1T1L1	maar	6	R	1,110	730	6.09E+05	3,125	0.658	0.629	0.784
39	4	Mechaferra	Bilate River Field	Ethiopia	221291	monogenetic volcanic field	7.040021	38.086103	1,545	5	G0R1T1L1	maar	6	R	1,030	775	5.98E+05	3,385	0.752	0.718	0.656
40	5	Bishoftu Guda	Bishoftu Volcanic Field	Ethiopia	221220	fissure vents	8.787252	38.993312	1,880	3	G0R1T1L1	maar	6	R	1,075	895	7.40E+05	3,145	0.833	0.815	0.940
41	6	Kiroftu	Bishoftu Volcanic Field	Ethiopia	221220	fissure vents	8.778577	39.000554	1,880	3	G0R1T1L1	maar	6	R	480	425	1.80E+05	1,560	0.885	0.995	0.929
42	7	Hora	Bishoftu Volcanic Field	Ethiopia	221220	fissure vents	8.761578	38.992982	1,870	3	G0R1T1L1	maar	6	R	1,730	1,065	1.15E+06	4,650	0.616	0.489	0.668
43	8	Bishoftu	Bishoftu Volcanic Field	Ethiopia	221220	fissure vents	8.741218	38.982556	1,865	3	G0R1T1L1	maar	6	R	1,405	1,005	9.86E+05	3,810	0.715	0.636	0.854
44	9	K'oftu	Bishoftu Volcanic Field	Ethiopia	221220	fissure vents	8.832824	39.049267	1,935	3	G0R1T1L1	maar	6	R	2,060	1,325	1.73E+06	5,515	0.643	0.519	0.715
45	10	Ora Kilole	Bishoftu Volcanic Field	Ethiopia	221220	fissure vents	8.802948	39.083407	1,890	3	G0R1T1L1	maar	6	R	1,130	1,120	8.86E+05	3,500	0.991	0.883	0.909
46	11	Green Lake	Bishoftu Volcanic Field	Ethiopia	221220	fissure vents	8.702293	38.975288	2,020	4	G0R1T1L1	maar	6	R	945	785	5.94E+05	2,895	0.831	0.847	0.891
47	12	Dendi	Dendi Volcano	Ethiopia	nd	stratovolcano	8.838066	38.018077	2,836	5	G1R1T1L1	crater	6	R	2,415	2,005	3.84E+06	7,370	0.830	0.838	0.888
48	13	Wonchi	Wonchi Volcano	Ethiopia	nd	stratovolcano	8.792317	37.894222	2,881	5	G1R1T1L1	crater	6	R	3,010	2,025	4.23E+06	19,485	0.673	0.594	0.140
49	14	Abijatta	O'a Caldera/Shala Caldera	Ethiopia	221280	caldera	7.610656	38.602238	1,581	5	G1R1T0L1	caldera	6	R	12,110	7,040	7.45E+07	36,580	0.581	0.647	0.700
50	15	Shala	O'a Caldera/Shala Caldera	Ethiopia	221281	caldera	7.455807	38.530774	1,559	5	G1R1T0L1	caldera	6	R	24,885	14,765	3.01E+08	96,535	0.593	0.619	0.406
51	16	Langano	O'a Caldera/Shala Caldera	Ethiopia	221282	caldera	7.6015	38.750534	1,587	5	G1R1T0L1	caldera	6	R	21,385	14,150	2.31E+08	85,760	0.662	0.643	0.395
52	17	Chitu	O'a Caldera/Shala Caldera	Ethiopia	221283	monogenetic volcanic field	7.403362	38.420227	1,563	5	G0R1T0L1	maar	6	R	1,225	635	7.19E+05	3,470	0.518	0.610	0.750

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TABLE 1 | (*Continued*) The VOLADA_Africa 2.0 database, mentioning the lake number (#), the number of lakes in the same country (#/country), the lake name, the volcano the depends on, the country, GVP number (Global Volcanism Program number https://volcano.si.edu/search_volcano.cfm), volcano type, the latitude and longitude (Lat. and Long. in decimal coordinates), the elevation above sea level (m a.s.l.), level of study (1–5, *see* text for details), genetic class (*see* text for details), lake type, physical and chemical classification, length of major and minor lake axes (Dmajor and Dminor, respectively, in m), lake surface area (A, in m^2), lake perimeter (in meter), Aspect Ratio (AR, Eq. 1), Elongation (EL, Eq. 2), Isoperimetric Circularity (IC, Eq. 3).

#	#/Country	Lake	Volcano	Country	GVP number	Volcano type	Lat.	Long.	Elevation (m asl)	Level of study	Genetic class	Lake type	Phys. Class	Chem. Class	D major (m)	D minor (m)	A (m^2)	Perimeter (m)	AR	EL	IC
53	18	Zengena	nd	Ethiopia	nd	monogenetic volcanic field	10.913149	36.966771	2,515	5	G0R1T1L1	maar	6	R	840	710	4.55E+05	2,575	0.845	0.821	0.862
54	19	Dembel	Mt Zuquala	Ethiopia	nd	stratovolcano	8.542033	38.855155	2,835	5	G1R1T1L1	crater	6	R	570	370	1.65E+05	1,675	0.649	0.647	0.739
55	1	Rutundu	Mount Kenya	Kenya	nd	stratovolcano	−0.042483	37.463922	3,082	5	G1R1T0L1	crater	6	R	460	220	9.58E+04	1,220	0.478	0.576	0.809
56	2	Hohnel	Mount Kenya	Kenya	nd	stratovolcano	−0.181993	37.289730	4,215	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	455	165	7.19E+04	1,195	0.363	0.442	0.633
57	3	Hidden Tarn	Mount Kenya	Kenya	nd	stratovolcano	−0.180470	37.315102	4,248	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	235	175	3.32E+04	690	0.745	0.765	0.876
58	4	Carr Lakes (2)	Mount Kenya	Kenya	nd	stratovolcano	−0.180857	37.345558	3,965	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	340	215	5.35E+04	1,050	0.632	0.589	0.610
59	5	Enchanted Lake	Mount Kenya	Kenya	nd	stratovolcano	−0.171586	37.335677	4,251	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	290	175	4.21E+04	865	0.603	0.637	0.707
60	6	Thompson's Tarn (2)	Mount Kenya	Kenya	nd	stratovolcano	−0.168623	37.320388	4,324	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	175	125	1.39E+04	530	0.714	0.578	0.622
61	7	Gallery Tarn	Mount Kenya	Kenya	nd	stratovolcano	−0.163570	37.324651	4,462	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	190	65	1.03E+04	490	0.342	0.363	0.539
62	8	Teleki Tarn	Mount Kenya	Kenya	nd	stratovolcano	−0.168669	37.305970	4,296	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	275	180	3.52E+04	845	0.655	0.593	0.619
63	9	Lewis Tarn	Mount Kenya	Kenya	nd	stratovolcano	−0.161640	37.310524	4,587	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	135	90	1.05E+04	495	0.667	0.734	0.538
64	10	Tyndall Tarn	Mount Kenya	Kenya	nd	stratovolcano	−0.156321	37.304172	4,472	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	125	60	5.18E+03	345	0.480	0.422	0.547
65	11	Two Tarn	Mount Kenya	Kenya	nd	stratovolcano	−0.156825	37.299391	4,500	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	220	110	1.95E+04	650	0.500	0.513	0.580
66	12	Nanyuki Tarn	Mount Kenya	Kenya	nd	stratovolcano	−0.155001	37.297260	4,489	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	105	65	6.90E+03	445	0.619	0.797	0.438
67	13	Emerald Tarn	Mount Kenya	Kenya	nd	stratovolcano	−0.152130	37.294431	4,346	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	160	125	1.26E+04	475	0.781	0.627	0.702
68	14	Curling Pond	Mount Kenya	Kenya	nd	stratovolcano	−0.158445	37.314575	4,784	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	40	20	5.00E+02	100	0.500	0.398	0.628
69	15	Square Tarn	Mount Kenya	Kenya	nd	stratovolcano	−0.153876	37.323172	4,656	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	45	25	1.01E+03	125	0.556	0.635	0.812
70	16	Harris Tarn	Mount Kenya	Kenya	nd	stratovolcano	−0.151465	37.319496	4,760	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	70	50	2.74E+03	195	0.714	0.712	0.905
71	17	Simba Tarn	Mount Kenya	Kenya	nd	stratovolcano	−0.148504	37.322257	4,601	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	60	40	1.71E+03	195	0.667	0.605	0.565
72	18	Lower Simba Tarn	Mount Kenya	Kenya	nd	stratovolcano	−0.144637	37.319092	4,412	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	65	20	9.69E+02	165	0.308	0.292	0.447
73	19	Kami Tarn	Mount Kenya	Kenya	nd	stratovolcano	−0.144204	37.310072	4,457	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	45	35	1.05E+03	165	0.778	0.660	0.485
74	20	Oblong Tarn	Mount Kenya	Kenya	nd	stratovolcano	−0.145151	37.301596	4,368	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	190	85	1.58E+04	540	0.447	0.557	0.681
75	21	Hausberg Tarn	Mount Kenya	Kenya	nd	stratovolcano	−0.144125	37.300256	4,364	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	195	60	1.06E+04	500	0.308	0.355	0.533
76	22	Polish Man's Tarn	Mount Kenya	Kenya	nd	stratovolcano	−0.137082	37.295502	4,433	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	70	60	3.66E+03	240	0.857	0.951	0.798
77	23	Hanging Tarn	Mount Kenya	Kenya	nd	stratovolcano	−0.155306	37.332563	4,443	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	130	100	1.06E+04	420	0.769	0.799	0.755
78	24	Michaelson	Mount Kenya	Kenya	nd	stratovolcano	−0.146236	37.351426	3,958	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	425	325	1.18E+05	1,370	0.765	0.832	0.790
79	25	Hall Tarns (5)	Mount Kenya	Kenya	nd	stratovolcano	−0.143371	37.345343	4,288	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	250	100	1.61E+04	820	0.400	0.328	0.301
80	26	Ellis	Mount Kenya	Kenya	nd	stratovolcano	−0.123114	37.400612	3,461	5	G0R0T0L0	glacial lakes in volcanic environment	6	R	795	195	1.14E+05	1,835	0.245	0.230	0.425
81	27	Alice	Mount Kenya	Kenya	nd	stratovolcano	−0.075265	37.464472	3,557	5	G1R1T0L1	crater	6	R	725	280	1.98E+05	1,890	0.386	0.480	0.697
82	28	Sacred Lake	Mount Kenya	Kenya	nd	stratovolcano	0.047764	37.527992	2,350	5	G0R1T1L1	maar (ephemeral)	6	R	950	755	5.55E+05	2,975	0.795	0.783	0.788
83	29	Tilapia Lake (3)	Central Island	Kenya	222010	tuff cones	3.488834	36.042356	363	5	G0R1T1L1	maar	6	R	295	220	5.69E+04	935	0.746	0.833	0.818
84	30	unnamed	S Shore Lake Turkana	Kenya	nd	tuff cone?	2.415791	36.594737	364	5	G0R1T1L1	maar	6	R	265	255	5.19E+04	850	0.962	0.941	0.903
85	31	Lake Paradise	Marsabit	Kenya	222021	shield volcano	2.205042	37.931401	848	5	G0R1T1L1	maar	6	R	690	440	2.36E+05	2,560	0.638	0.631	0.453
86	32	Crater Pan	Marsabit	Kenya	222021	shield volcano	2.309932	37.969263	1,481	5	G0R1T1L1	maar	6	R	360	290	8.81E+04	1,110	0.806	0.866	0.899
87	33	Marsabit County	Marsabit	Kenya	222021	shield volcano	2.359822	37.999918	1,309	5	G0R1T1L1	maar	6	R	400	270	6.63E+04	1,140	0.675	0.528	0.641
88	34	Crescent Island crater	Lake Naivasha	Kenya		nd	−0.767585	36.408114	1,885	5	G0R1T1L1	maar	6	R	15,805	11,885	1.45E+08	77,460	0.752	0.739	0.304
89	35	Sonachi	W of Lake Naivasha	Kenya	nd	nd	−0.811956	36.278151	1,885	3	G0R1T1L1	maar	5	R	2,945	2,135	5.44E+06	9,840	0.725	0.799	0.706
90	36	Crater Lake	nd (NW of Lake Sonachi)	Kenya	nd	nd	−0.782813	36.262700	1,896	5	G0R1T1L1	maar	6	R	660	310	1.45E+05	1,860	0.470	0.424	0.527
91	37	Simbi	S of Nyanza Gulf. Lake Victoria	Kenya		nd	−0.3673	34.629500	1,145	5	G0R1T1L1	maar	6	R	800	525	3.30E+05	2,245	0.656	0.657	0.823

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#	#/Country	Lake	Volcano	Country	GVP number	Volcano type	Lat.	Long.	Elevation (m asl)	Level of study	Genetic class	Lake type	Phys. Class	Chem. Class	D major (m)	D minor (m)	A (m^2)	Perimeter (m)	AR	EL	IC
92	1	Waw an Namus lake	SE of Al Haruj Volcanic Field	Libya	nd	nd	24.907923	17.75182	366	5	G1R1T1L1	crater	6	R	600	260	1.24E+05	1,815	0.433	0.439	0.473
93	1	Farihy Mahery	Ambre Bobaomby	Madagascar	233011	monogenetic volcanic field	−12.44058	49.244097	365	5	G0R1T1L1	maar	6	R	554	420	1.73E+05	2,295	0.758	0.718	0.413
94	2	Maharasika	Ambre Bobaomby	Madagascar	233011	monogenetic volcanic field	−12.534767	49.177112	1,062	5	G0R1T1L1	maar	6	R	255	240	3.87E+04	805	0.941	0.758	0.750
95	3	Matsabory Taranta	Ambre Bobaomby	Madagascar	233011	monogenetic volcanic field	−12.584105	49.149962	1,252	5	G0R1T1L1	maar	6	R	690	515	3.41E+05	2,285	0.746	0.912	0.821
96	4	Matsabory Malio	Ambre Bobaomby	Madagascar	233011	monogenetic volcanic field	−12.597774	49.16064	1,335	5	G0R1T1L1	maar	6	R	385	285	8.53E+04	1,090	0.740	0.733	0.902
97	5	Matsabory Manonja	Ambre Bobaomby	Madagascar	233011	monogenetic volcanic field	−12.625977	49.177434	1,035	5	G0R1T1L1	maar	6	R	620	600	2.51E+05	2,145	0.968	0.831	0.686
98	6	Matsabory Ampatan' Ambohitra	Ambre Bobaomby	Madagascar	233011	monogenetic volcanic field	−12.696976	49.167929	811	5	G0R1T1L1	maar	6	R	800	680	3.96E+05	2,505	0.850	0.788	0.793
99	7	Farihy Antanavo +1	Farihy Antanavo	Madagascar	nd	nd	−12.750169	49.25451	368	5	G0R1T1L1	maar	6	R	1,650	1,280	1.58E+06	4,865	0.776	0.739	0.839
100	8	Farihy Andjavibe	Nosy Be Island	Madagascar	233012	pyroclastic cones	−13.295901	48.22352	19	5	G0R1T1L1	maar	6	R	745	555	3.30E+05	2,685	0.745	0.757	0.575
101	9	3 unnamed	Nosy Be Island	Madagascar	233012	pyroclastic cones	−13.30949	48.238826	155	5	G0R1T1L1	maar	6	R							
102	10	Farihy Bemapaza	Nosy Be Island	Madagascar	233012	pyroclastic cones	−13.317878	48.237747	236	5	G0R1T1L1	maar	6	R	520	510	1.86E+05	1,770	0.981	0.876	0.746
103	11	Farihy Maintimasoa	Nosy Be Island	Madagascar	233012	pyroclastic cones	−13.313355	48.222779	89	5	G0R1T1L1	maar	6	R	595	495	2.31E+05	2,125	0.832	0.831	0.643
104	12	Farihy Amparihibe	Nosy Be Island	Madagascar	233012	pyroclastic cones	−13.32023	48.211217	71	5	G0R1T1L1	maar	6	R	1,645	1,210	1.64E+06	5,755	0.736	0.772	0.622
105	13	Farihy Antisidihy	Nosy Be Island	Madagascar	233012	pyroclastic cones	−13.328442	48.219704	94	5	G0R1T1L1	maar	6	R	725	610	3.27E+05	2,680	0.841	0.792	0.572
106	14	Farihy Antasahamanavaka	Nosy Be Island	Madagascar	233012	pyroclastic cones	−13.327408	48.243759	214	5	G0R1T1L1	maar	6	R	895	635	4.55E+05	2,790	0.709	0.723	0.735
107	15	Farihy Djabala	Nosy Be Island	Madagascar	233012	pyroclastic cones	−13.38642	48.242435	44	5	G0R1T1L1	maar	6	R	435	315	1.01E+05	1,560	0.724	0.680	0.522
108	16	Farihy Ampombilava	Nosy Be Island	Madagascar	233012	pyroclastic cones	−13.394032	48.244096	25	5	G0R1T1L1	maar	6	R	555	415	1.89E+05	1,985	0.748	0.781	0.603
109	17	Andraikiba	Tritrivakely/ Vakinankaratra	Madagascar	233015	pyroclastic cones	−19.874453	46.969582	1,517	5	G0R1T1L1	maar	6	R	1,090	820	9.19E+05	4,005	0.752	0.985	0.720
110	18	Tritriva	Tritrivakely/ Vakinankaratra	Madagascar	233015	pyroclastic cones	−19.929119	46.924657	1,730	5	G0R1T1L1	maar	6	R	335	105	2.49E+04	785	0.313	0.283	0.508
111	19	Itasy	Itasy Volcanic Field	Madagascar	233014	pyroclastic cones	−19.065851	46.785701	1,221	5	G0R1T1L1	maar	6	R	7,450	7,005	3.22E+07	55,335	0.940	0.739	0.132
112	20	unnamed	Itasy Volcanic Field	Madagascar	233014	pyroclastic cones	−18.920348	46.716762	1,192	5	G0R1T1L1	maar	6	R	425	255	9.46E+04	1,335	0.600	0.667	0.667
113	21	unnamed	Itasy Volcanic Field	Madagascar	233014	pyroclastic cones	−18.923107	46.726122	1,224	5	G0R1T1L1	maar	6	R	370	95	5.94E+04	1,335	0.257	0.552	0.419
114	22	Andranotoraha	Itasy Volcanic Field	Madagascar	233014	pyroclastic cones	−18.949398	46.742226	1,292	5	G0R1T1L1	maar	6	R	415	345	1.18E+05	1,395	0.831	0.872	0.762
115	23	unnamed	Itasy Volcanic Field	Madagascar	233014	pyroclastic cones	−18.999815	46.72934	1,224	5	G0R1T1L1	maar	6	R	320	170	4.91E+04	900	0.531	0.611	0.762
116	24	unnamed	Itasy Volcanic Field	Madagascar	233014	pyroclastic cones	−19.010321	46.735777	1,239	5	G0R1T1L1	maar	6	R	200	170	2.62E+04	605	0.850	0.834	0.899
117	25	unnamed	Itasy Volcanic Field	Madagascar	233014	pyroclastic cones	−19.015673	46.752733	1,232	5	G0R1T1L1	maar	6	R	635	500	2.53E+05	2,085	0.787	0.799	0.731
118	26	unnamed	Itasy Volcanic Field	Madagascar	233014	pyroclastic cones	−19.017943	46.728016	1,232	5	G0R1T1L1	maar	6	R	630	390	2.17E+05	2,215	0.619	0.696	0.556
119	27	unnamed	Itasy Volcanic Field	Madagascar	233014	pyroclastic cones	−19.131751	46.644018	1,176	5	G0R1T1L1	maar	6	R	340	280	7.32E+04	1,170	0.824	0.806	0.672
120	28	unnamed	Itasy Volcanic Field	Madagascar	233014	pyroclastic cones	−19.184869	46.646128	1,159	5	G0R1T1L1	maar	6	R	190	125	1.67E+04	555	0.658	0.589	0.681
121	1	Bisoke	Bisoke	Rwanda	223050	Stratovolcano	−1.460855	29.486841	3,600	4	G1R1T1L1	crater	6	R	305	290	6.97E+04	1,055	0.951	0.954	0.787
122	2	Muhavura	Muhavura	Rwanda-Uganda	223060	Stratovolcano	−1.382938	29.677872	4,101	5	G1R1T1L1	crater	6	R	28	27	5.60E+02	90	0.964	0.909	0.869
123	1	Deriba (2 lakes)	Caldera of Jebel Marra	Sudan	225030	volcanic field	12.950006	24.258121	2,195	5	G1R1T1L1	crater	6	R	1,150	805	7.71E+05	3,590	0.700	0.742	0.752
124	2	Malha	Meidob Volcanic Field	Sudan	225050	volcanic field	15.131185	26.171321	816	3	G1R1T1L1	maar	6	R	180	170	2.43E+04	575	0.944	0.955	0.924
125	1	Empakaai	Ngorongoro District	Tanzania	nd	caldera	−2.911639	35.839853	2,224	5	G1R1T1L1	crater	6	R	3,195	2,695	7.60E+06	10,460	0.844	0.948	0.873
126	2	Magadi	Ngorongoro District	Tanzania	nd	caldera	−3.183485	35.531512	1,732	5	G1R1T0L1	crater	6	R	3,840	2,280	6.86E+06	14,140	0.594	0.592	0.431
127	4	Masoko (6 lakes)	Rungwe Volcanic Province	Tanzania	222170	volcanic field	−9.334192	33.755974	861	5	G0R1T1L1	maar	6	R	700	675	3.73E+05	2,335	0.964	0.969	0.860
128	5	Ngozi	Ngozi	Tanzania	222164	caldera	−9.007995	33.553284	2,073	5	G1R1T1L1	crater	3	G-R	2,585	1770	3.22E+06	10,910	0.685	0.614	0.340
129	6	Chala	Chala	Tanzania-Kenya	nd	caldera	−3.318714	37.699070	879	5	G1R1T0L1	caldera	6	R	2,685	1955	4.24E+06	9,635	0.728	0.749	0.574
130	6	Duluti	S of Mt Meru	Tanzania	nd	nd	−3.386342	36.788415	1,276	3	G0R1T1L1	maar	6	R	1,110	740	5.77E+05	3,210	0.667	0.596	0.704
131	1	Kitagata	Katwe-Kikorongo	Uganda	223003	monogenetic volcanic field	−0.063042	29.97496	919	3	G0R1T1L1	maar	6	R	1,020	940	7.10E+05	3,095	0.922	0.869	0.931
132	2	Murumuli/Murumuu	Katwe-Kikorongo	Uganda	223003	monogenetic volcanic field	−0.074275	29.990778	915	3	G0R1T1L1	maar	6	R	575	510	2.37E+05	2,065	0.887	0.913	0.698
133	3	Nyamanyuka	Katwe-Kikorongo	Uganda	223003	monogenetic volcanic field	−0.090866	29.98787	905	3	G0R1T1L1	maar	6	R	1,065	950	8.04E+05	3,255	0.892	0.903	0.954
134	4	Bunyampaka	Katwe-Kikorongo	Uganda	223003	monogenetic volcanic field	−0.040083	30.130152	879	3	G0R1T1L1	maar	6	R	460	425	1.55E+05	1,430	0.924	0.933	0.952
135	5	Katwe	Katwe-Kikorongo	Uganda	223003	monogenetic volcanic field	−0.126605	29.868967	882	3	G0R1T1L1	maar	6	R	2,550	940	2.55E+06	8,595	0.369	0.499	0.434
136	6	Kikorongo/Queens Pavilion	Katwe-Kikorongo	Uganda	223003	monogenetic volcanic field	−0.007435	30.012397	914	3	G0R1T1L1	maar	6	R	1,975	1,165	1.58E+06	5,765	0.590	0.516	0.597
137	7	Mahega	Katwe-Kikorongo	Uganda	223003	monogenetic volcanic field	−0.014307	29.96674	918	3	G0R1T1L1	maar	6	R	495	415	1.63E+05	1,580	0.838	0.847	0.820
138	8	Munyanyange	Katwe-Kikorongo	Uganda	223003	monogenetic volcanic field	−0.135756	29.885665	912	3	G0R1T1L1	maar	6	R	650	465	2.92E+05	2,040	0.715	0.880	0.882
139	9	Maseche	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.094429	30.192868	910	3	G0R1T1L1	maar	6	R	655	535	3.30E+05	2,945	0.817	0.979	0.478
140	10	Bagusa	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.100193	30.178101	910	3	G0R1T1L1	maar	6	R	885	700	4.57E+05	2,620	0.791	0.743	0.837
141	11	Kyambura	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.11037	30.213959	923	3	G0R1T1L1	maar	6	R	890	770	4.71E+05	2,655	0.865	0.757	0.840
142	12	unnamed1.2.3	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.125192	30.191811	922	3	G0R1T1L1	maar (ephemeral)	6	R	255	105	2.52E+04	700	0.412	0.493	0.646
143	13	Nshenyi	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.150209	30.159715	953	3	G0R1T1L1	maar	6	R	1,120	710	5.90E+05	3,710	0.634	0.599	0.539
144	14	Chibwera	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.153153	30.142931	977	3	G0R1T1L1	maar	6	R	1,115	960	8.17E+05	3,465	0.861	0.837	0.855
145	15	Mbugo	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.174004	30.156157	980	3	G0R1T1L1	maar	6	R	770	645	3.70E+05	2,445	0.838	0.795	0.778
146	16	Kyamwiga	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.18637	30.145129	1,024	3	G0R1T1L1	maar	6	R	2,320	1,370	3.13E+06	8,925	0.591	0.740	0.494
147	17	Bugwagi	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.1941	30.188127	1,058	3	G0R1T1L1	maar	6	R	1,095	750	6.26E+05	3,085	0.685	0.665	0.827

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TABLE 1 | (*Continued*) The VOLADA_Africa 2.0 database, mentioning the lake number (#), the number of lakes in the same country (#/country), the lake name, the volcano the depends on, the country, GVP number (Global Volcanism Program number https://volcano.si.edu/search_volcano.cfm), volcano type, the latitude and longitude (Lat. and Long. in decimal coordinates), the elevation above sea level (m a.s.l.), level of study (1–5, *see* text for details), genetic class (*see* text for details), lake type, physical and chemical classification, length of major and minor lake axes (Dmajor and Dminor, respectively, in m), lake surface area (A, in m^2), lake perimeter (in meter), Aspect Ratio (AR, Eq. 1), Elongation (EL, Eq. 2), Isoperimetric Circularity (IC, Eq. 3).

#	#/Country	Lake	Volcano	Country	GVP number	Volcano type	Lat.	Long.	Elevation (m asl)	Level of study	Genetic class	Lake type	Phys. Class	Chem. Class	D major (m)	D minor (m)	A (m^2)	Perimeter (m)	AR	EL	IC
148	18	Katinda	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.222514	30.105217	1,042	3	G0R1T1L1	maar	6	R	840	690	4.44E+05	2,635	0.821	0.801	0.804
149	19	Mirambi	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.2289	30.106164	1,085	3	G0R1T1L1	maar	6	R	925	820	5.75E+05	2,960	0.886	0.856	0.825
150	20	Kariya	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.232341	30.160604	1,253	3	G0R1T1L1	maar	6	R	1,325	645	8.53E+05	4,535	0.487	0.619	0.521
151	21	Nyungu	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.258352	30.094193	1,186	3	G0R1T1L1	maar	5b2?	R	655	345	2.04E+05	1,940	0.527	0.605	0.681
152	22	Mafuro	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.266708	30.102212	1,275	3	G0R1T1L1	maar	6	R	525	495	1.90E+05	1,700	0.943	0.878	0.826
153	23	Luijono	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.272808	30.085096	1,268	3	G0R1T1L1	maar	6	R	1,120	685	5.57E+05	3,110	0.612	0.565	0.724
154	24	Kyasanduka	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.289252	30.051001	1,013	3	G0R1T1L1	maar	6	R	980	595	5.29E+05	3,045	0.607	0.701	0.717
155	25	Nyamusingire	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.288466	30.028927	984	3	G0R1T1L1	maar	6	R	3,470	1745	4.09E+06	12,425	0.503	0.433	0.333
156	26	Kigezi	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.287449	30.109972	1,313	3	G0R1T1L1	maar	6	R	445	315	1.03E+05	1,340	0.708	0.662	0.721
157	27	Mugogo	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.285688	30.125189	1,322	3	G0R1T1L1	maar	6	R	1875	475	1.22E+06	7,715	0.253	0.442	0.258
158	28	Kako	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.307614	30.097811	1,411	3	G0R1T1L1	maar	6	R	600	365	1.97E+05	1,770	0.608	0.697	0.790
159	29	Nkugute	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.324301	30.098871	1,411	3	G0R1T1L1	maar	6	R	1,355	720	9.54E+05	5,545	0.531	0.662	0.390
160	30	Murabio	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.33551	30.036281	1,116	3	G0R1T1L1	maar	6	R	715	395	2.77E+05	2,285	0.552	0.690	0.667
161	31	Kacuba	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.344124	30.030834	1,132	3	G0R1T1L1	maar	6	R	355	270	6.82E+04	1,140	0.761	0.689	0.659
162	32	Karolero	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.342163	30.024982	1,116	3	G0R1T1L1	maar	6	R	960	735	5.80E+05	3,040	0.766	0.801	0.789
163	33	Kyogo	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.341566	30.019982	1,126	3	G0R1T1L1	maar	6	R	185	180	2.30E+04	660	0.973	0.856	0.663
164	34	Chema	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.256705	30.117617	1,271	3	G0R1T1L1	maar	6	R	1,060	900	7.26E+05	3,400	0.849	0.823	0.789
165	35	Kamweru	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.259025	30.124511	1,282	3	G0R1T1L1	maar	6	R	680	410	2.40E+05	1,970	0.603	0.661	0.777
166	36	Kasirya	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.25905	30.131988	1,296	3	G0R1T1L1	maar	6	R	475	265	1.20E+05	1,525	0.558	0.677	0.648
167	37	Kamunzuka	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.262087	30.156326	1,287	3	G0R1T1L1	maar	6	R	575	525	2.44E+05	2,070	0.913	0.940	0.716
168	38	Kabarogi	Bunyaruguru	Uganda	223004	monogenetic volcanic field	−0.229048	30.21549	1,363	3	G0R1T1L1	maar	6	R	725	575	2.91E+05	2,355	0.793	0.705	0.659
169	39	Nyamirina	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.519526	30.318823	1,505	3	G0R1T1L1	maar	6	R	590	435	1.86E+05	2,015	0.737	0.680	0.576
170	40	Nyinabulitwa	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.510415	30.322963	1,427	3	G0R1T1L1	maar	6	R	950	465	3.81E+05	2,930	0.489	0.538	0.558
171	41	Nkuruba	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.5171	30.302842	1,518	3	G0R1T1L1	maar	6	R	285	130	2.51E+04	1,185	0.456	0.393	0.225
172	42	Nyabikere	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.496664	30.32771	1,384	3	G0R1T1L1	maar	6	R	940	520	4.43E+05	3,495	0.553	0.638	0.456
173	43	Nyanswiga	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.506321	30.287665	1,478	3	G0R1T1L1	maar	6	R	260	125	3.12E+04	1,190	0.481	0.588	0.277
174	44	Nyahira	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.498907	30.286612	1,455	3	G0R1T1L1	maar	6	R	225	145	2.81E+04	870	0.644	0.707	0.467
175	45	Lyantonde	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.489147	30.280036	1,407	3	G0R1T1L1	maar	6	R	475	385	1.40E+05	1,745	0.811	0.790	0.578
176	46	Nyinambuga	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.479359	30.289753	1,366	3	G0R1T1L1	maar	6	R	1,360	485	5.82E+05	4,215	0.357	0.401	0.412
177	47	Rukwanzi	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.47683	30.278245	1,341	3	G0R1T1L1	maar	6	R	385	300	9.22E+04	1,380	0.779	0.792	0.608
178	48	Katanda	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.48065	30.262707	1,345	3	G0R1T1L1	maar	6	R	780	655	3.93E+05	2,755	0.840	0.822	0.651
179	49	Mwegenyi	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.489331	30.262118	1,401	3	G0R1T1L1	maar	6	R	975	665	3.33E+05	3,235	0.682	0.446	0.400
180	50	Mwamba	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.462061	30.274514	1,304	3	G0R1T1L1	maar	6	R	1,060	440	4.19E+05	4,620	0.415	0.475	0.247
181	51	Mbajo	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.449373	30.274308	1,265	3	G0R1T1L1	maar	6	R	500	360	1.60E+05	1,935	0.720	0.815	0.537
182	52	Lugembe	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.448728	30.281302	1,295	3	G0R1T1L1	maar	6	R	420	290	8.75E+04	1,310	0.690	0.632	0.641
183	53	Ndicho	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.446313	30.269921	1,269	3	G0R1T1L1	maar	6	R	385	300	9.61E+04	1,400	0.779	0.826	0.616
184	54	Rwenjuba	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.441383	30.266734	1,254	3	G0R1T1L1	maar	6	R	665	465	2.15E+05	2,275	0.699	0.619	0.522
185	55	Mubiro	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.439453	30.253723	1,214	3	G0R1T1L1	maar	6	R	650	405	1.87E+05	2,030	0.623	0.564	0.570
186	56	Nyarayabana	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.429438	30.249043	1,192	3	G0R1T1L1	maar	6	R	455	390	1.12E+05	1,455	0.857	0.689	0.665
187	57	Nyamugoro	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.449911	30.241177	1,281	3	G0R1T1L1	maar	6	R	405	365	1.11E+05	1,540	0.901	0.862	0.588
188	58	Nyamiteza	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.435937	30.225592	1,263	3	G0R1T1L1	maar	6	R	730	620	3.00E+05	2,440	0.849	0.717	0.633
189	59	Nyamugosani	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.424384	30.229734	1,228	3	G0R1T1L1	maar	6	R	415	335	1.01E+05	1,255	0.807	0.747	0.806
190	60	Wankenzi	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.420011	30.26604	1,168	3	G0R1T1L1	maar	6	R	665	400	1.94E+05	2,485	0.602	0.559	0.395
191	61	Wandakara	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.417167	30.270892	1,169	3	G0R1T1L1	maar	6	R	310	125	3.63E+04	845	0.403	0.481	0.639
192	62	Kitere	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.398254	30.27139	1,142	3	G0R1T1L1	maar	6	R	540	160	1.12E+05	1,590	0.296	0.489	0.557
193	63	Ntambi	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.410681	30.230353	1,169	3	G0R1T1L1	maar	6	R	685	620	3.19E+05	2,560	0.905	0.866	0.612
194	64	Kanyamukali	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.400376	30.234127	1,162	3	G0R1T1L1	maar	6	R	510	295	1.20E+05	1,530	0.578	0.587	0.644
195	65	Kyanga	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.400234	30.234193	1,163	3	G0R1T1L1	maar	6	R	510	295	1.20E+05	1,530	0.578	0.587	0.644
196	66	Murigamire	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.42051	30.286289	1,201	3	G0R1T1L1	maar	6	R	685	665	2.78E+05	2,335	0.971	0.754	0.641
197	67	Kanyabutetere	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.415455	30.288305	1,200	3	G0R1T1L1	maar	6	R	130	125	1.22E+04	435	0.962	0.919	0.810
198	68	Murusi	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.42729	30.292303	1,226	3	G0R1T1L1	maar	6	R	540	490	2.23E+05	1,895	0.907	0.974	0.780
199	69	Kasenda	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.431837	30.290425	1,247	3	G0R1T1L1	maar	6	R	335	280	6.99E+04	1,035	0.836	0.793	0.820
200	70	Kanyamansira	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.416434	30.305052	1,198	3	G0R1T1L1	maar	6	R	315	160	4.00E+04	960	0.508	0.513	0.545
201	71	Kerere	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.419421	30.309173	1,205	3	G0R1T1L1	maar	6	R	760	590	3.13E+05	2,615	0.776	0.690	0.575
202	72	Kyerbwato	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.431286	30.323265	1,231	3	G0R1T1L1	maar	6	R	575	225	1.20E+05	1,775	0.391	0.462	0.479
203	73	Kanyanchu	Ndali-Kasenda	Uganda	223001	monogenetic volcanic field	0.433931	30.323854	1,249	3	G0R1T1L1	maar	6	R	170	125	1.87E+04	525	0.735	0.824	0.853
204	74	Kyaninga	Fort Portal	Uganda	223001	monogenetic volcanic field	0.700409	30.297701	1,540	3	G0R1T1L1	maar	5b1	R	895	265	2.98E+05	3,630	0.296	0.474	0.284
205	75	Ekikoto	Fort Portal	Uganda	223001	monogenetic volcanic field	0.701051	30.314185	1,544	3	G0R1T1L1	maar	6	R	195	150	2.02E+04	910	0.769	0.676	0.307
206	76	Kayihara	Fort Portal	Uganda	223001	monogenetic volcanic field	0.702266	30.316305	1,549	3	G0R1T1L1	maar	6	R	100	80	5.66E+03	465	0.800	0.721	0.329
207	77	Kaitabarago	Fort Portal	Uganda	223001	monogenetic volcanic field	0.693624	30.262095	1,558	3	G0R1T1L1	maar	6	R	220	120	2.52E+04	800	0.545	0.663	0.495
208	78	Saka	Fort Portal	Uganda	223001	monogenetic volcanic field	0.689259	30.240581	1,567	3	G0R1T1L1	maar	6	R	1,350	420	5.61E+05	6,430	0.311	0.392	0.171
209	79	Nyabikora	Fort Portal	Uganda	223001	monogenetic volcanic field	0.687741	30.233634	1,575	3	G0R1T1L1	maar	6	R	350	290	7.80E+04	1,120	0.829	0.811	0.781
210	80	Kyegere	Fort Portal	Uganda	223001	monogenetic volcanic field	0.681489	30.235666	1,569	3	G0R1T1L1	maar	6	R	510	350	1.24E+05	1,740	0.686	0.607	0.515
211	81	Kibengo	Lake George	Uganda	nd	monogenetic volcanic field	−0.107156	30.215242	925	5	G0R1T1L1	maar	6	R	895	735	4.70E+05	2,975	0.821	0.747	0.667
212	1	A Pot/Mazafim	Annobon Island	Equitorial Guinea	nd	shield. caldera. pyroclastic cones	−1.425709	5.632444	258	5	G1R1T1L1	crater	6	R	770	660	4.15E+05	2,650	0.857	0.891	0.743

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TABLE 1 | (*Continued*) The VOLADA_Africa 2.0 database, mentioning the lake number (#), the number of lakes in the same country (#/country), the lake name, the volcano the depends on, the country, GVP number (Global Volcanism Program number https://volcano.si.edu/search_volcano.cfm), volcano type, the latitude and longitude (Lat. and Long. in decimal coordinates), the elevation above sea level (m a.s.l.), level of study (1–5, *see* text for details), genetic class (*see* text for details), lake type, physical and chemical classification, length of major and minor lake axes (Dmajor and Dminor, respectively, in m), lake surface area (A, in m^2), lake perimeter (in meter), Aspect Ratio (AR, Eq. 1), Elongation (EL, Eq. 2), Isoperimetric Circularity (IC, Eq. 3).

#	#/Country	Lake	Volcano	Country	GVP number	Volcano type	Lat.	Long.	Elevation (m asl)	Level of study	Genetic class	Lake type	Phys. Class	Chem. Class	D major (m)	D minor (m)	A (m^2)	Perimeter (m)	AR	EL	IC
213	2	Moca	Bioko	Equitorial Guinea	224003	shield. caldera. pyroclastic cones	3.357009	8.62453	1,818	5	G1R1T1L1	crater	6	R	895	755	5.00E+05	2,830	0.844	0.795	0.785
214	1	Queen's Mary Peak	Tristan da Cunha	United Kingdom	386010	shield. pyroclastic cones. lava domes	−37.109115	−12.288894	1,954	5	G1R1T1L1	crater	6	R	85	65	4.16E+03	285	0.765	0.733	0.644
215	2	Bottom Pond	Tristan da Cunha	United Kingdom	386010	shield. pyroclastic cones. lava domes	−37.07359	−12.262347	614	5	G0R1T1L1	maar	6	R	220	145	2.47E+04	695	0.659	0.650	0.643
216	3	Middle Pond	Tristan da Cunha	United Kingdom	386010	shield. pyroclastic cones. lava domes	−37.077374	−12.264395	616	5	G0R1T1L1	maar	6	R	240	200	3.52E+04	835	0.833	0.778	0.634
217	4	Top Pond	Tristan da Cunha	United Kingdom	386010	shield. pyroclastic cones. lava domes	−37.080559	−12.266451	733	5	G0R1T1L1	maar	6	R	165	90	1.28E+04	590	0.545	0.599	0.462
218	1	Karthala	Karthala	Comores	233010	shield volcano	−11.765959	43.365019	2,017	3	G1R1T1L1	crater (ephemeral)	6	R	260	235	4.53E+04	770	0.904	0.853	0.960
219	2	Dziani Boundouni	Mohéli Island	Comores	nd	maar	−12.378908	43.849209	20	5	G0R1T1L1	maar	6	R	700	330	2.11E+05	2,470	0.471	0.548	0.435
220	3	Dziani Dzaha	Mayotte	Comores	nd	maar	−12.770823	45.288824	6	5	G0R1T1L1	maar	6	R	675	400	2.12E+05	1,770	0.593	0.593	0.851
-	Average																		0.693	0.691	0.654
-	stdev																		0.179	0.166	0.185

lake: crater lake (G1R1T1L1), caldera lake (G1R1T0L1), maar-diatreme lake (G0R1T1L1), geothermal lake (G0-1R1T1L0-1), lake in a volcanic environment (G1R0T0L0), lake dammed by volcanic deposits (G0-1R0-1T0-1L0), volcanic lake after snow melting (G0-1R1T1L1), and the generic "volcanic lake" covering the entire range of lake types (G0-1R0-1T0-1L0-1). This "grassroots" classification scheme, especially adapted to shed light on the poorly studied lakes, will now be applied to VOLADA, starting with an update for the African lakes (VOLADA_Africa 2.0) (**Table 1**).

The chemical classification system (G-versus R-dominated, Varekamp et al., 2000) was maintained here, despite the poor knowledge on lake water chemistry of the African lakes. Gas-dominated lakes (G) are generally found in craters of (highly) active volcanoes, with low-pH and heated water bodies that result from gas and vapor input from the underlying magmatic-hydrothermal system. Rock-dominated lakes (R) host water with a purely meteoric origin that attained equilibrium through water-rock interaction with the host rock that composes the lake basin. As the gas-dominated lakes are often easily recognized by their color (turquoise, green, blue-green, white, grey, or even yellow; Christenson et al., 2015), or the presence of evaporation plumes coming off their surface, in the absence of this characteristic feature the lakes were, arguably correctly, classified as R-dominated. Apparently, Africa does not host gas-dominated, "erupting," peak-, high- and medium-activity lakes, hence, all lakes are R-dominated (**Table 1**). The physical classification system by Rouwet et al. (2014) (simplified from Pasternack and Varekamp, 1997) is adopted here: *1*) erupting (i.e. hot, hyper-saline and ultra-acidic (pH near 0) lakes breached periodically by phreatic or phreatomagmatic eruptions), *2*) peak-activity (i.e. heated, saline and acidic (pH < 2 lakes topping actively degassing magmatic systems), *3*) high activity (a and b, for higher and lower solutes contents, respectively) (i.e. saline and acidic (pH < 2) lakes showing evidence of heating and passively degassing hydrothermal systems; e.g. steam heated SO_4-rich lakes), *4*) medium activity (a and b, for higher and lower solutes contents, respectively) (i.e. lakes with low heating and input from an underlying hydrothermal system, but not composed of purely meteoric water), *5*) low activity (a and b1/b2, for higher and lower solutes contents, respectively, i.e. non-acidic lakes generally with evidence of input of CO_2-rich fluids), *6*) no activity (i.e. lakes composed of purely meteoric water without any evidence of a degassing hydrothermal system). Noteworthy, lake class "5b2" points to the potentially hazardous "Nyos-type" lakes.

The level of study (a numerical scale from 1 to 5) of volcanic lakes is revised here, following the new criteria: (1) monitored, (2) well studied in the scientific literature, (3) few scientific publications available, (4) no publications, but web-sourced information available, (5) no information available, at all.

African volcanic lakes are well studied in terms of micro- and macrobiology of the water, and palynology, microfacies analyses (climate studies), dating, stable isotopic composition, and non-terrestrial biological records of cores from lake sediments, among other topics (e.g. Gasse and Van Campo, 1998, 2001; Williamson et al., 1999; Barker et al., 2000; Rumes et al., 2005; Eggermont

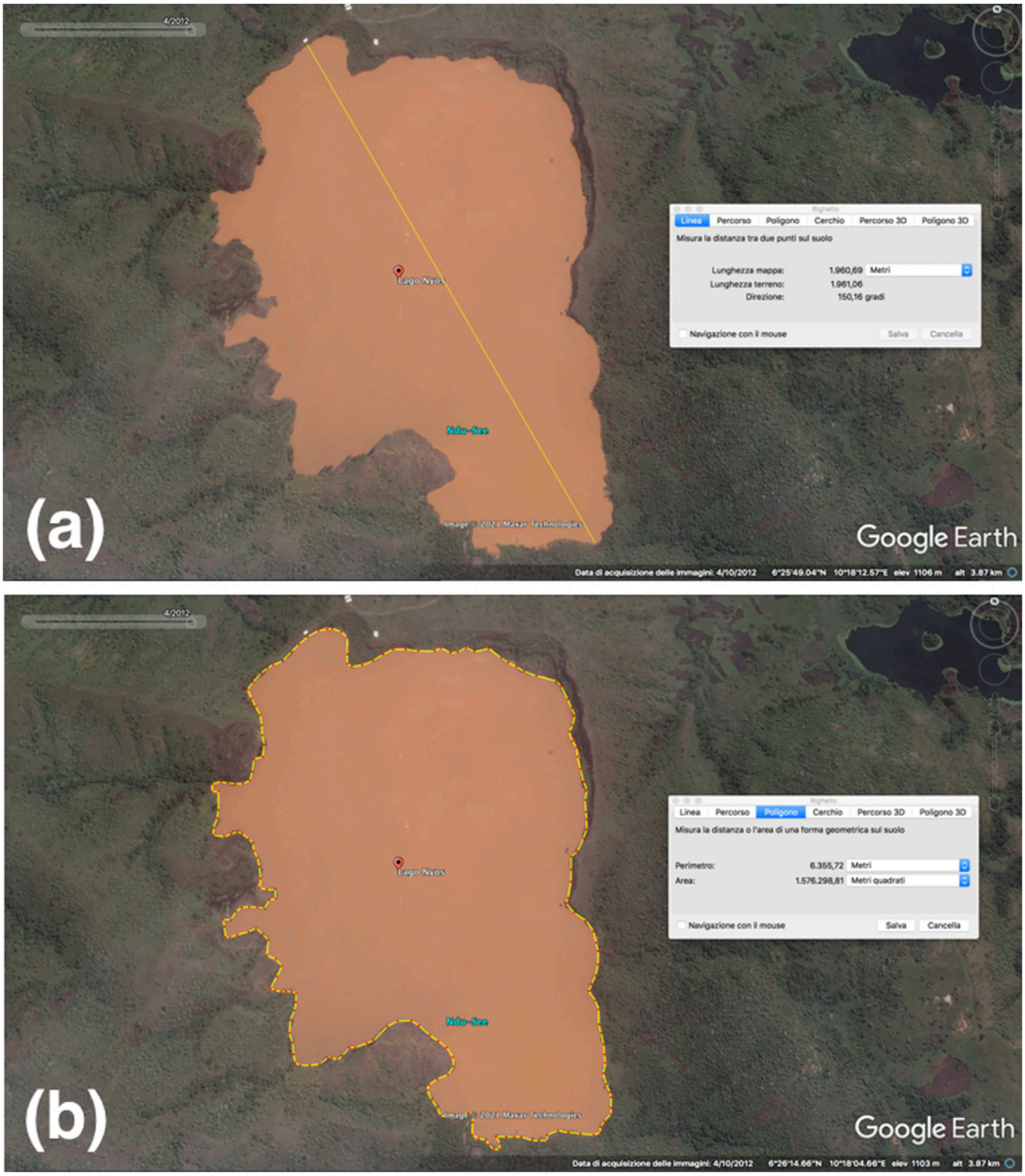

FIGURE 2 | (A) Ruler option to measure distances in GoogleEarth, **(B)** Polygone option to measure circumferences and surface areas in GoogleEarth (image© Maxar Technologies).

et al., 2006; Delalande et al., 2008; Kebede et al., 2009; Lemma, 2009; Russell et al., 2009; Cocquyt et al., 2010; Giresse and Makaya-Mvoubou, 2010; Ndebele-Murisa et al., 2010; Ryves et al., 2011; Garcin et al., 2012, 2014; Lebamba et al., 2016). These numerous studies sometimes revealed useful details, but their goals are outside the scope of the present review that aims to provide a better database on the volcanic lakes's physical limnology and volcanology, to convert VOLADA_Africa 2.0 into a useful tool to better assess future volcanic hazards related to the African volcanic lakes (Aka et al., 2017). The physical volcanology and petrogenetic aspects of some lake-hosting areas, however, have largely increased our insights in single cases (Chapman et al., 1998; Barker et al., 2000; Freeth and Rex, 2000; Anema and Fesselet 2003; Haileab et al., 2004; Deruelle et al., 2007; Aka et al., 2008, 2018; Ngwa et al., 2010; Bruhn et al., 2011; Nkouandou and Temdjim, 2011; Ngos and Giresse, 2012; Temdjim, 2012; Aka and Yokoyama, 2013; Tchamabe et al., 2013; Rufer et al., 2014; Asaah et al., 2015; Delalande-Le Mouëllic et al.,

FIGURE 3 | Panoramic view of Lake Nyos, Cameroon, showing the system of the three artificial degassing pipes near the horizon (picture by DR).

2015; Balashova et al., 2016; Pouclet et al., 2016; Jolie, 2019; Venturi et al., 2019). Nevertheless, the general number of these studies remains limited in many areas.

The African volcanic lakes were pin-pointed by decimal coordinates by scanning the Earth's surface through GoogleEarthPro (https://www.google.it/intl/it/earth/index.html) and OpenStreetMap (https://www.openstreetmap.org/) web sources (**Figure 1**), resulting in an interactive VOLADA-Africa 2.0 spreadsheet (**Table 1**), free available through VHub (https://vhub.org/groups/iavceicvl/resources). Lakes were ordered by country. Where available, the GVP number (http://volcano.si.edu/search_volcano.cfm) (Global Volcanism Program), its elevation above sea level, and the volcano and type of volcano the lake belongs to, are reported. Holocene volcanoes are exported on the map in **Figure 1** from the Global Volcanism Program; it is apparent that not all volcanic lakes coincide with Holocene active volcanoes, which implies that *1*) not all the lakes belong to Holocene active volcanoes, or *2*) the date of the last eruptions from the reported lakes is unknown.

A recent study by Graettinger (2018) deduced dimensionless morphometric parameters (ratios) to better describe maar *crater* morphology. The use of ratios provides the benefit to represent lake shape, regardless of the absolute dimensions of the craters. We here apply the same approach for the *lake* morphology of the 220 volcanic lakes in Africa, through the "ruler" and "polyogone" tools in GoogleEarthPro (**Figure 2**), with an accuracy of ± 5 m (**Table 1**; **Figure 2**). The Aspect Ratio (AR) is the ratio between the lake's minor (Dmin) and major (Dmax) diameter, with the minor diameter perpendicular to the major diameter:

$$AR = D_{min}/D_{max} \quad (1)$$

An AR closer to 1 implies an equant distance from the center of the lake.

The Elongation (EL) instead relates the area of a circle with the measured major diameter to the surface area of the lake (A). EL better describes asymmetrical morphologies compared to AR.

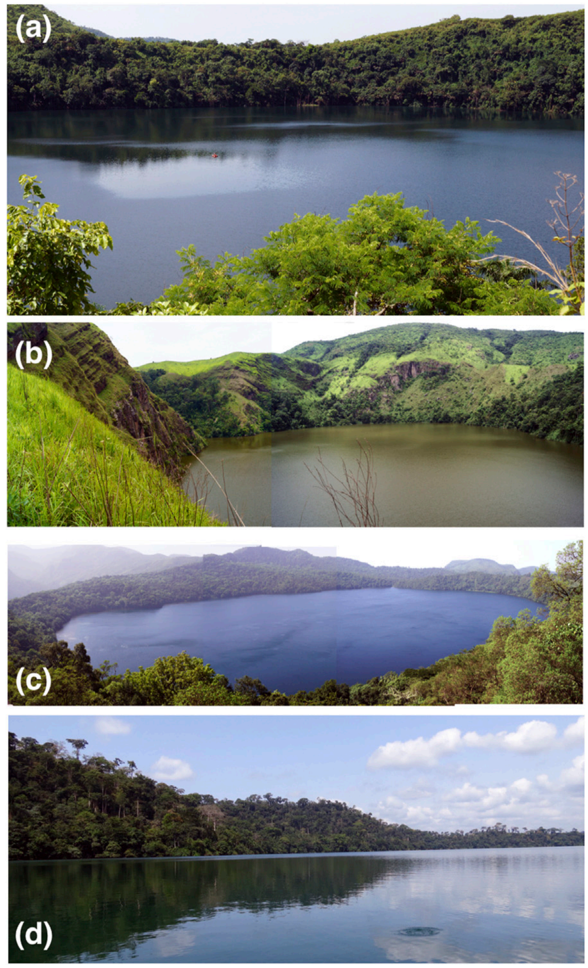

FIGURE 4 | Views of the Cameroonian maar lakes **(A)** Elum, **(B)** Enep, **(C)** Oku and **(D)** Barombi Mbo (pictures **(A–C)** by Issa, picture **(D)** by DR).

$$EL = A/\left[\pi\,(Dmax/2)^2\right] \quad (2)$$

The Isoperimetric Circularity (IC) compares the lake surface area with the area (A) of a circle with the same perimeter (p):

$$IC = 4\pi A\,/p^2 \quad (3)$$

Perfectly circu ar lake shapes have IC values near 1 or equal to 1, whereas lake shapes with a varying angle of curvature along their perimeter deviate further from 1.

A simple statistical approach (histograms) of the morphometric data for the African volcanic *lakes* is applied and compared to the data provided by Graettinger (2018) for *maar craters* in the world.

VOLADA_Africa 2.0: Country by Country

The updated database VOLADA_Africa 2.0 (**Table 1**) counts a significantly higher number (220) of volcanic lakes in Africa, compared to the 97 lakes in the original version of VOLADA (Rouwet et al., 2014). This large difference results mainly from the inclusion of numerous lakes in Uganda, Kenya, and Madagascar, previously not counted. Volcanic lakes in Africa are often located in remote and/or low population density regions (**Figure 1**). The country with most volcanic lakes is Uganda (81), followed by Kenya (37), Cameroon (33), Madagascar (28), Ethiopia (19), Tanzania (6), the minor islands (i.e. Annobon, Bioko and Tristan da Cunha, West of the continent; and Karthala, Mohéli and Mayotte, Southeast of the continent, (9), Rwanda (2), Sudan (2), D.R. Congo (2), and Libya (1).

Cameroon

The pioneering study by Kling (1988) on the limnology of 39 Cameroonian lakes, of which 33 are of volcanic origin, forms the basis of the revised catalogue for Cameroon. Recent insights on the chemical and stable isotopic composition of 17 of the 33 Cameroonian volcanic lakes came from Issa et al. (2014), which followed the cataloguing philosophy adopted by Kling (1988), and our current study. Needless to say, Lakes Nyos (**Figure 3**) and Monoun are arguably two of the most studied volcanic lakes on Earth. Well studied aspects for Lakes Nyos and Monoun are:

(5) the degassing dynamics of the 1984 and 1986 gas bursts (Freeth and Kay, 1987; Kling et al., 1987; Sigurdsson et al., 1987; Barberi et al., 1989; Kanari, 1989; Tazieff, 1989; Freeth, 1990; Freeth, 1992; Evans et al., 1993; Freeth, 1994);
(6) the hazard assessment mainly based on the chemistry of lake water and dissolved gases (Sano et al., 1987, 1990; Tuttle et al., 1987; Kling et al., 1989; Kusakabe et al., 1989, 2000, 2008; Lockwood and Rubin, 1989; Giggenbach, 1990; Nojiri et al., 1990, 1993; Faivre Pierret et al., 1992; Kusakabe and Sano, 1992; Tietze, 1992; Evans et al., 1993, 1994; Kantha and Freeth, 1996; Tanyileke et al., 1996; Nagao et al., 2010; Yoshida et al., 2010; Issa et al., 2014; Tassi and Rouwet, 2014; Anazawa et al., 2019; Kusakabe et al., 2019);
(7) the risk mitigation through artificial degassing (since 2001, intensified since 2011 and ongoing; Halbwachs and Sabroux, 2001; Halbwachs et al., 1993, 2004, 2020; McCord and Schladow, 1998; Schmid et al., 2003, 2004, 2006; Kling et al., 2005; Ohba et al., 2017; Saiki et al., 2017; Yoshida et al., 2017);
(8) the dam stability and its recent (2014–2015) reinforcement (Lockwood et al., 1988; Freeth and Rex, 2000; Aka et al., 2008; Aka and Yokoyama, 2013; Fantong et al., 2015; Tanyileke et al., 2019);
(9) the topic of numerous projects (e.g. NyMo degassing, France-Cameroon; SATREPS, Japan-Cameroon), studies and review papers (Aka, 2015; Kling et al., 2015; Kusakabe, 2015, 2017; Tanyileke et al., 2019).

Besides Lake Nyos and Lake Monoun, the Oku Volcanic Field in NW Cameroon (**Figure 1C**) hosts 13 other maar lakes (**Table 1**). Lake Wum (Kusakabe et al., 1989), near the homonymous city (>80,000 inhabitants), and Lake Bambuluwe (Freeth, 1990) were subjected to a vertical sampling soon after the Lake Nyos gas burst, and resulted gas-free and not-heated from below. The remaining 12 lakes of the Oku Volcanic Field (i.e. Baleng, Banefo, Bambili, Benakuma, Elum – **Figure 4A**, Enep – **Figure 4B**, Mfouet, Nchout, Nyi, Negop Baghang, Oku – **Figure 4C**, and Kuk) are less studied (**Table 1**; Issa et al., 2014).

During the 9th Workshop of the IAVCEI Commission on Volcanic Lakes (March 2016), Barombi Mbo (Maley et al., 1990; Kling et al., 1991; Tchamabe et al., 2013; **Figure 4D**), the maar lake with the largest surface area in Cameroon (**Table 1**), was subjected to a pioneering physical limnological and fluid geochemical survey. Within the philosophy of the "Nyos bias," lowering CTD probes and water and dissolved gas sampling along the vertical profile of the 110 m deep lake, revealed that the gas stored in deep lake strata is far from reaching near-threshold pressures to cause a limnic gas burst. This "non-result" does have strong implications on the hazard assessment for the inhabited shores of Barombi Mbo, and the nearby city of Kumba (>125,000 inhabitants). The three remaining maar lakes in the Tombel Graben (Dissoni, the only 5 m deep Barombi Koto and Mboandang) are less studied (Kling, 1988; Issa et al., 2014).

Mt Manengouba, a 2,411 m high shield volcano overlain by a stratovolcano located in the Northern sector of the Tombel Graben, is probably the second most famous volcano in Cameroon after the active Mt Cameroon (Pouclet et al., 2014). The 3 km wide caldera hosts two "twin crater lakes," Manengouba Male and Manengouba Female (**Figure 5**). The dark colored Manengouba Female is the second deepest volcanic lake in Cameroon (168 m), after Lake Nyos, while Manengouba Male is 90 m deep and green colored inside a steep-walled crater basin. Both lakes are inactive and fed by meteoric water, hence the color difference is explained by different microbial activity (Issa et al., 2014) reported, however, a weak degassing activity of Mt Manengouba, stressing the need for a monitoring setup for these summit crater lakes.

The Debunscha lakes (big and small, 7.27×10^4 m^2 and 3.51×10^3 m^2, respectively) are small maars located a few hundred meters from the Atlantic Ocean at the foot of Mt Cameroon. The massive amounts of rainfall in the coastal area (12,000 mm of

FIGURE 5 | The Manengouba Female (left – black) and Manengouba Male (right – green) crater lakes of Mt Manengouba (Cameroon; picture by P. Hernández).

FIGURE 6 | Crater lake of Mt Bisoke (Rwanda) (November 2013; picture by SC).

rain/year; Issa et al., 2014) and strong winds change the isotopic composition of the lake water, despite being in mass balance equilibrium with the meteoric rain input (13.5 m deep, Debunscha big). Their nearness to the ocean (<50 m), and at the center of the most active sector of the Cameroon Volcanic Line (CVL hereafter; Aka et al., 2001, 2004) between Mt Cameroon and the island of Bioko, suggests that the Debunscha maar lakes were formed by phreatomagmatic eruptions from satellite vents of Mt Cameroon interacting with seawater inside the coastal aquifers (Ngwa et al., 2010, 2017).

To the Northeastern extent of the CVL seven maar lakes are located near the city of Ngaoundéré (>260,000 inhabitants in 2005) in the Volcanic Plateau of Adamawa (Aka et al., 2018; and references therein). Kling (1988) put them on the map by studying their basic physical limnological characteristics, while recently Issa et al., 2014 tackled them for their stable isotopic composition of the water. Given its unique location between the Sahel and the sub-equatorial rainforest, paleoclimate during the Pleistocene-Holocene was reconstructed in recent studies (Ngos and Giresse, 2012; N'nanga et al., 2019), based on the geochemistry and mineralogy of sediments from Lake Fonjak, Mbalang and Tizong. Issa et al. (this topic collection) demonstrated a high similarity to Lakes Nyos and Monoun, and suggest that these seven lakes should become a priority in future monitoring efforts.

D.R. Congo

Lac Vert, less than 2 km north of the western sector of the Lake Kivu main basin (**Figures 1A,B**), fills up the central sector (695–385 m) of three nested craters, interpreted as a maar complex. Lake Kivu, a major rift lake of the Western branch of the East African Rift (EAR hereafter), creates an ideal hydrological and tectonic setting to create phreatomagmatic volcanism near its shores. Poppe et al. (2016) emphasized the importance of phreatomagmatic volcanism from a hazard point of view in the area between Lake Kivu and the famous, active volcanoes of the Virunga Volcanic Province: Nyamulagira and Nyiragongo. Moreover, Lac Vert is situated northeast of the Kabuno Basin, the northwestern sub-basin of Lake Kivu that is almost cut off entirely from Lake Kivu. The Kabuno Basin area is characterized by more magmatic gas signatures ($^3He/^4He$ ratios of 5.4 Ra), and the inland degassing features tend to have similar degassing sources as Nyiragongo ($^3He/^4He$ ratios of 8.7 Ra): Sake (west of Lac Vert, $^3He/^4He$ ratios of 7.7 Ra) and the CO_2-rich degassing areas (Mazukos, $^3He/^4He$ ratios of 8.4 Ra; Tedesco et al., 2010; Vaselli et al., 2015) towards Lac Vert. The depth of Lac Vert is unknown; CTD measurements and water and gas sampling along the vertical profiles still lack.

A small lake partially occupies the Kirunga tuff ring, less than 100 m from the Lake Kivu shore. Kirunga is one of the 15 eruptive centers recognized along the northern shore of Lake Kivu, here occasionally filled by a lake (Poppe et al., 2016). Besides the direct gas hazard that could originate from the lakes (Lac Vert), the occurrence of renewed phreatomagmatic volcanism due to effective magma-water interaction with Lake Kivu is not excluded in the future for the densely inhabited Goma area, home to at least 750.000 people (note: at the moment of writing, the crisis of Nyiragongo volcano is ongoing, and includes this proposed scenario as one of the related hazardous outcomes).

Ethiopia

The maar lakes in the Bishoftu Volcanic Field in Central Ethiopia (**Figure 1A**) have been studied during the early 1960s for their physical limnology (Wood et al., 1976). They were recognised to turn over in winter (December), and do not show a stable stratification. A recent biolimnological study by Lemma (2009) on Lake Hora (35 m deep) and Lake Bishoftu Guda (55 m deep) show a seasonal decrease in temperature from 22–23°C at the surface to 20–21°C at depth. Anoxic environments set in below 5–10 m depth. These physical characteristics demonstrate that the "Bishoftu lakes" are unstably stratified, solar heated and highly sensitive to seasonal, and even diurnal variations. From the hazard point of view, this implies that these lakes are inefficient in storing CO_2 in their bottom waters, regardless of the fact that this recharge effectively occurs, which does not seem to be the case. The city of Debre Zenit (approx. 100,000 inhabitants) surrounding the lakes is hence not exposed to possible Nyos-type hazards.

FIGURE 7 | Lake Empakaai (seen from the southwest), Northern Tanzania (picture by B. Fontaine). Volcanoes in the back are Oldoinyo Lengai (left) and Kerimasi (right).

The lakes in the Butajiri Silti and Bilate River Fields are unreported in the scientific literature (level of study 5). A geodynamic model for the Butajiri Silti Field was proposed by Hunt et al. (2020), however, they did not enter in detail on the existence of volcanic lakes in the area (e.g. Ara Shetan, **Table 1**).

Mt Dendi is an inactive volcano peaking at 3,260 m a.s.l. with a 4 km-wide caldera like crater. Inside this crater, a peculiar dumbbell-shaped lake filled with meteoric water is hosted. Still, in the Central highlands of Ethiopia, 13.5 km Southwest of Mt Dendi a similarly shaped volcano, Mt Wonchi (3,450 m a.s.l.) houses an irregular-shaped crater lake that fills part of the 4.5 km wide summit caldera, also host to hot springs. Nevertheless, both large edifice volcanoes are inactive, and hence their crater lakes do not seem to be a topic of interest regarding natural hazard assessment. The extinct Mt Zuqualla volcano, 40 km south of Ethiopia's capital Addis Abeba, hosts Dembel crater lake.

The strongly rift-related soda Lakes Shala, Langano, Chitu and Abijatta are arguably maar lakes (Le Turdu et al., 1999). The maar Lake Shala is approximately 87 m deep (max depth 266 m) and has a pH ranging from 9.8 to 10.2, depending on the season. No clear stratification appears, coinciding with the fact that "soda lakes" are often sensitive to external changes (Osato et al., 2016). Lake Zengena appears to be a small solitary maar lake (approx. 450 m diameter) towards the Lake Tana wetlands area in Northwestern Ethiopia.

Kenya

Of the 33 volcanic lakes in Kenya (**Figure 1A**), 27 are located on the flanks of the inactive (eruptive period between 3.1 and 2.6 Ma) large-edifice stratovolcano, Mt Kenya (5,199 m a.s.l.), the second highest mountain in Africa, after Kilimanjaro, in Tanzania. The volcano does not show a clear summit crater, and all lakes appear to be distributed in satellite vents and craters, or filled-up glacial depressions on the volcano flank (Loomis et al., 2012). No data are available on the chemical and physical properties of these lakes. Hydrothermal activity is not reported for Mt Kenya.

Three peculiar maar lakes (Tilapia lakes) are formed on the Central Island of Lake Turkana, a major rift lake in the EAR. These lakes are unstudied, but their setting and appearance suggest that they are formed by phreatomagmatic eruptions beneath Lake Turkana. Another unnamed maar-type lake is found near the southern shores of Lake Turkana.

The shield volcano Marsabit (1,707 m a.s.l.), towards Northern Kenya, is dotted by 22 maars, three of which are recognized to contain lakes. No further information is available on these maar lakes.

"Crater Lake" just East of the large freshwater (non-volcanic) Lake Naivasha fills in a third of a maar. Lake Naivasha is a large (150 km^2), shallow (17 m) basin fed by extended aquifers (wetland) (Yihdego and Becht, 2013; Fazi et al., 2018), that arguably provided an aquifer through which phreatomagmatic eruptions breached, giving origin to the "Crater Lake," or Lake Sonachi. The temperature and alkalinity increase with depth (max 7 m) at Lake Sonachi, which suggests sublacustrine input of alkaline springs. Despite its shallow depth, Lake Sonachi is permanently stratified (meromixis) at depth due to the high content of organic carbon, but mixes its upper water layers even in day-night cycles. The high pH (9.5) limits CO_2 dissolution in bottom waters, where instead a CH_4 environment reigns (Venturi et al., 2019). Lake Sonachi is an exotic, small "bio-activity" crater lake (Cabassi et al., 2014; Rouwet, 2021).

Libya

Miocene to recent intracontinental volcanic fields compose distinct landforms in Libya's Sahara region. In these volcanic fields, monogenetic volcanic bodies, such as scoria and spatter cones, are the most dominant volcano types; however, broad craters with low rims are commonly interpreted as maar volcanoes in spite that most of them are dry, or host only shallow playa lakes. In Al Haruj al Abyad broad maar-like depressions are common (Németh, 2004; Martin and Németh, 2006; Cvetkovic et al., 2010; Bardintzeff et al., 2012).

The most recently active volcano in Southern Libya, Waw an Namus (**Figure 1A**), figures as a black dot of tephra in the Quaternary yellow sediments of the Sahara Desert (Bardintzeff et al., 2012). The volcano, a broad volcanic depression, is thought to be a satellite vent of the Al Haruj Volcanic Province to the North (Bardintzeff et al., 2012; Elshaafi and Gudmundsson, 2016, 107, 2018). Inside the 4 km-wide depression, inferred to be a maar volcano, a 150 m cone rises up to 547 m a.s.l. Three shallow, warm and saline lakes flank the base of the tephra cone. Although apparently young sulfur and (probably) alunite deposits are reported (Bardintzeff et al., 2012), there is no further mention of hydrothermal activity. We interpret the salinity and temperature of the three Waw an Namus crater (or intracaldera) lakes as resulting from solar heating and consequent steady evaporation, without further implications for volcanic hazard.

Madagascar

Considering their shapes, observed from satellite images, and their geology from rare studies (Rasamimanana et al., 1998; Bardintzeff et al., 2010; Rufer et al., 2014), the volcanic lakes in Madagascar appear to be maar lakes. From North to central

Madagascar, maar lakes are located in several volcanic fields: Ambre Bobaomby (six lakes), Farihy Antanavo (one single lake), Nosy Be Island (NW Madagascar, nine lakes), Tritrivakely (two lakes; Sibree, 1891; Gasse et al., 1994; Gasse and Van Campo, 1998, 2001; Williamson et al., 1998), and Itasy (10 lakes) (**Figure 1A**). Lake Itasy is an irregularly shaped large lake (6 × 7 km approx.), clearly composed of multiple craters, ruling out its origin as a caldera basin. Lake Itasy is surrounded by many smaller (unnamed) maars. Lake Tritriva shows that maar lakes are not necessarily circular or ellipse-shaped, as recently conveyed by Graettinger (2018), pointing to a multiple-vent origin and/or erosional enlargement due to landslides along the inner crater wall. To the best of our knowledge, no data are available on water chemistry, or physical limnological characteristics of the maar lakes in Madagascar.

Rwanda

In the shadows of the infamous volcanoes Nyiragongo and Nyamulagira, Mt Bisoke stratovolcano (3,711 m a.s.l.) straddles the border between Rwanda and D.R. Congo (Barette et al., 2017) (**Figures 1A,B**). The summit contains a circular shaped crater lake (**Figure 6**), with a diameter of approximately 300 m. The lake was sampled in November 2013 and analyzed for its water chemistry (by SC and Giovanni Bruno Giuffrida), whereas its water temperature varied from 10° to 15°C, with a measured pH of 6.27. The chemistry did not show any evidence of hydrothermal activity, reflected by very low SO_4 and Cl contents (<3 and <1 mg L-1, respectively), although a local guide reports on vague memories of the smell of sulfur close to the water surface. Despite this limited data set, we argue that Mt Bisoke is in a state of quiescence after it last erupted in 1957. If the volcano reawakens in the future, the physical and chemical properties of the crater lake are suspected to show variations, possibly detectable by satellite imagery (e.g. lake disappearance upon evaporation, color changes).

The tiny crater lake (27–28 m) at the >4,100 Muhavura stratovolcano in the Virunga Volcanic Province, at the border between Rwanda and Uganda, has well preserved its pollen-record for the Holocene (McGlynn et al., 2013), but does not show evidence of volcanic activity.

Sudan

The 3,042 m high Deriba Caldera is the most spectacular feature of the Jebel Marra Volcanic Field in the Darfur region of Western Sudan (Burton and Wickers, 1966; Hammerton, 1968; Vail, 1972; Davidson and Wilson, 1989; Franz et al., 1997) (**Figure 1A**). Inside the 5 km-wide steep-walled caldera, formed 3,500 yr B.P. during voluminous pumice fall eruptions, a 700 × 1000 m-wide crater lake fills a horseshoe-shaped crater. A second lake is formed to the Northeast, at the lower rim of the caldera, probably as an affluent basin of rain falling inside the caldera capture area. To the best of our knowledge, no limnological or geochemical information is available for the two crater lakes. Nevertheless, it is worth noting that fumarolic activity has been observed inside the caldera in relatively recent times (Burton and Wickers, 1966).

One of the approximately 700 vents of the Pliocene to Holocene Meidob Volcanic field in Western Sudan, 150 km Northeast of the Deriba Caldera (**Figure 1A**), hosts a 180 m-diameter maar lake, without manifestation of any activity. The small monogenetic Bayuda Volcanic Field (BVF; 480 km^2) about 700 km NE from the Meidob Volcanic Field, comprises at least 53 cinder cones and 15 maar volcanoes in the Bayuda desert of northern Sudan of Quaternary age. The largest maar (800 m in diameter and 386 m deep) in the area is the Hosh Ea Dalam (32°35′38,32″E, 18°24′29,07″N). None of the 15 maars has a permanent lake, and are only shallow "salt pans" (Almond et al., 1969; Lenhardt et al., 2018).

Tanzania

Two renowned volcanic lakes are located in the Ngorongoro Crater Highlands in Northern Tanzania (**Figure 1A**): Lake Empakaai (or Lake Emakat, **Figure 7**) and Lake Magadi. Empakaai crater lake is 79 m-deep and well studied for its palynology and paleoclimate record from water and sediment cores (Muzuka et al., 2004; Ryner et al., 2006). The lake water chemistry reflects a high salinity (Total Dissolved Solid contents between 12,000 and 14,000 mg L-1), with Na and K as main cationic solutes (500–600 mg L-1 and 400–500 mg L-1, respectively; Muzuka et al., 2004). This composition probably originates from water-rock interaction with trachytic and phonolitic magmas (Fontijn et al., 2012), consequently enriched by enhanced evaporation by solar heating. No clear evidence of a hydrothermal system exists to hypothesize alternatively.

Northeast of Lake Empakaai (**Figures 1A**, **7**), passing the famous natro-carbonatitic volcano Oldoinyo Lengai (Keller and Zaitsev, 2012), Lake Natron fills the rift depression towards the border with Kenya. Lake Natron is not a volcanic lake, but rather a "rift lake in a volcanic environment," and we hence choose to not include it in VOLADA_Africa 2.0 despite its particular chemistry resulting from the water-rock interaction with carbonatitic country rocks: Na-HCO_3-CO_3 with a pH as high as 9.5 (*see* Pecoraino et al., 2015, for a review,; Fazi et al., 2018). Lake Magadi, Southeast of Lake Empakaai, partially fills the almost 20 km-wide Ngorongoro crater and hosts a saline brine, similar to Lake Empakaai. The exotic water chemistry of the three lakes (Empakaai, Magadi and Natron) hence results from solute enrichment by evaporation from an endorheic basin after water-rock interaction with the exceptional host rocks of the Ngorongoro area.

Lake Chala is located on the lower Eastern flanks of Mt Kilimanjaro, Africa's highest peak, at an elevation of 880 m a.s.l., and is shared with Kenya (**Figure 1A**). We here classify Lake Chala as a caldera lake. The lake is 94 m deep and has a nearly triangular shape with a main diameter of approx. 2 km. Lake Chala has been well studied in recent years in terms of palynology and limnology (Barker et al., 2013; Buckles et al., 2014, 2016; van Bree et al., 2018), although volcanology-focussed information lacks. The stratification of the lake is highly sensitive to seasonal variations (e.g. multiple rainy "seasons" per year; van Bree et al., 2018), which makes us suspect that long-term accumulation of gases in bottom waters is strongly inhibited–if gas input occurs in the first place.

The maar lakes in Southern Tanzania (Lake Masoko and five others in the Rungwe Volcanic Province; Fontijn et al., 2012), near the northern shores of Lake Malawi, are relatively well studied for their hydrology, (paleo)limnology, isotopy and palynology (Williamson et al., 1999; Barker et al., 2000; Delalande et al., 2008). The small maar lakes are sensitive to climate changes and hence ideal to reconstruct paleoclimate in the region, and to store ash records of past volcanic eruptions in the area (Fontijn et al., 2012). As the lakes in Northern Tanzania, the six "Mbaka lakes" are saline; suspicion exists on a possible hydrothermal input from beneath these lakes, which invites to future fluid geochemical surveys and hazard analyses for the area.

Lake Ngozi (83 m deep) tops one of the three major volcanoes, the 2,620 m-high homonymous volcano, in the Northwestern part of the Rungwe Volcanic Province (Fontijn et al., 2012) (**Figure 1A**). The irregular shape of the 3 km-wide collapse caldera and its crater lake is in agreement with the presumed young age of the crater and the latest magmatic eruption (<1 ka; Fontijn et al., 2010). A pioneering study on the water chemistry of Lake Ngozi (Delalande-Le Mouëllic et al., 2015) hypothesizes that the lake is affected by geothermal input (Na-Cl-rich, Mg-poor) and hydrothermal activity (pH 6.4–6.9, SO_4-rich steam heated waters), similar to the caldera lakes in El Salvador (Cabassi et al., 2019; Rouwet, 2021). Dominant CO_2 degassing (δ13C-DIC from +2.8 to +5.8‰, Delalande-Le Mouëllic et al., 2015) is probably of magmatic origin as also suggested by the high $^3He/^4He$ ratios (7–8.3 Ra, de Moor et al., 2013). The absence of any thermal and chemical stratification and the high pCO_2 along the water column results in diffuse CO_2 degassing at the lake surface (Jolie, 2019). This CO_2 degassing is structurally controlled, along E-W trending faults at the southern parts of the caldera lake, near the presumably last eruptive vent (Fontijn et al., 2010). Funnel-shaped depressions along this fault reach lake bottom temperatures up to 89°C (i.e. near boiling at the elevation of the lake, 2,060 m a.s.l.) (Jolie, 2019). These findings suggest that Lake Ngozi is topping an active volcano that could escalate into unrest in the future. A similar, though more vigorous CO_2 degassing dynamics was observed at Kelud crater lake, Indonesia, prior to the 2007 dome extrusion eruption (Caudron et al., 2012).

Moreover, we can mention that there are many maar-like dry craters in Tanzania. The genetic origin of these maars is currently under debate, as they arguably seem to be inexplicable by the general phreatomagmatic model (Mattson and Tripoli, 2011; Berghuijs and Mattson, 2013). This alternative model would imply that they could have been water filled during wet periods. Dry maars are, however, a recurrent feature in monogenetic volcanic fields, in Africa and elsewhere.

Uganda

The 81 volcanic lakes in Uganda are distributed in four volcanic fields: the Bunyaruguru (30 lakes) and Katwe-Kikorongo (eight lakes) Volcanic Fields in the South, near the EAR rift lakes George and Edward, and Ndale-Kasenda (36 lakes) and Fort Portal (seven lakes) Volcanic Fields in the North (Rumes et al., 2005; Stoppa and Schiazza, 2013) (**Figures 1A,B**). All the 81 lakes are classified as maar lakes (Melack, 1978). An early study by Mungoma (1990) revealed that the lake water chemistry of eight lakes in the Katwe-Kikorongo (Kikorongo, Nyamunyuka, Katwe, Bunyampaka and Kitagata; Lowenstein and Russell, 2011) and Bunyaruguru (Maseshe, Bagusa, Mahega) are highly saline (Conductivity 16.3 to 455 mS cm-1) and alkaline (pH 9–10.5), caused by water-rock interaction and enhanced evaporation of the generally small and shallow maar lakes. Solar heating results in mesothermal stratification of the studied lakes, shown by inverted vertical temperature profiles. Three water types are distinguished: carbonate-chloride- and chloride-type lakes in the Katwe-Kikorongo, and carbonate-sulfate-type lakes in Bunyaruguru.

In their turn, the deeper lakes in Uganda (e.g. Lake Kyaninga, 220 m deep, the largest lake in the Fort Portal Volcanic Field) seem to be geothermally heated, as shown by heated bottom waters. Lake Kyaninga is arguably meromictic (i.e. permanently stratified) below 100 m depth (Cocquyt et al., 2010). The particular chemistry, with high Cl, HCO_3 and SO_4 concentrations (up to 149, 108 and 64 mg L-1, respectively), rises curiosity on generic processes behind their formation and the need for renewed hypotheses and conceptual models, regarding natural hazard assessment. A recent study by De Crop and Verschuren (2019) on 11 maar lakes in Uganda stressed that high-frequency monitoring of physical-chemical parameters along water columns in tropical lakes is a must to better understand water mixing at various time scales (days to decades). The limnological control on water mixing can have implications on hazard, especially when gas or heat enters lake bottoms.

African Minor Islands

Peculiarly, some of the minor islands around the African continent host volcanic lakes. The islands of Bioko and Annobon (Equitorial Guinea) are shield volcanoes along the ocean-ward side of the CVL (Aka et al., 2001, 2004) (**Figures 1A,C**), topped by crater lakes Moca and Pot, respectively. Bioko, together with Mt Cameroon, is considered the most active centre of the CVL (Aka et al., 2004).

In the summit crater of Queen's Mary Peak (2,060 m a.s.l.), on the remote island of Tristan da Cunha (a British Overseas Territory, South Atlantic) (**Figure 1A**), a heart-shaped shallow lake filled with meteoric water is present (**Figure 8A**), whereas three aligned maar lakes (**Figure 8B**) –called "the ponds" by the locals (1, 2, 3 in **Figure 8C**)– are found on the Northeastern lower flank of the stratovolcano. The peculiar setting might teach us that maar volcanoes can form on top of composite polygenetic volcanoes, if the environment (e.g. ground-water and/or surface water availability) is favorable to produce explosive magma-water interaction (Kereszturi et al., 2011, 2014; Smith and Németh, 2017; Geshi et al., 2019). In the case of Tristan da Cunha, the maar lakes could have been formed by magma interacting with the incursion of marine water into the near-coastal aquifer (Németh and Cronin, 2009, 2011). The last eruptive activity that occurred in 1961–1962 did not originate from the summit crater, but on a coastal plateau near the northern shores of the island (Baker et al., 1964).

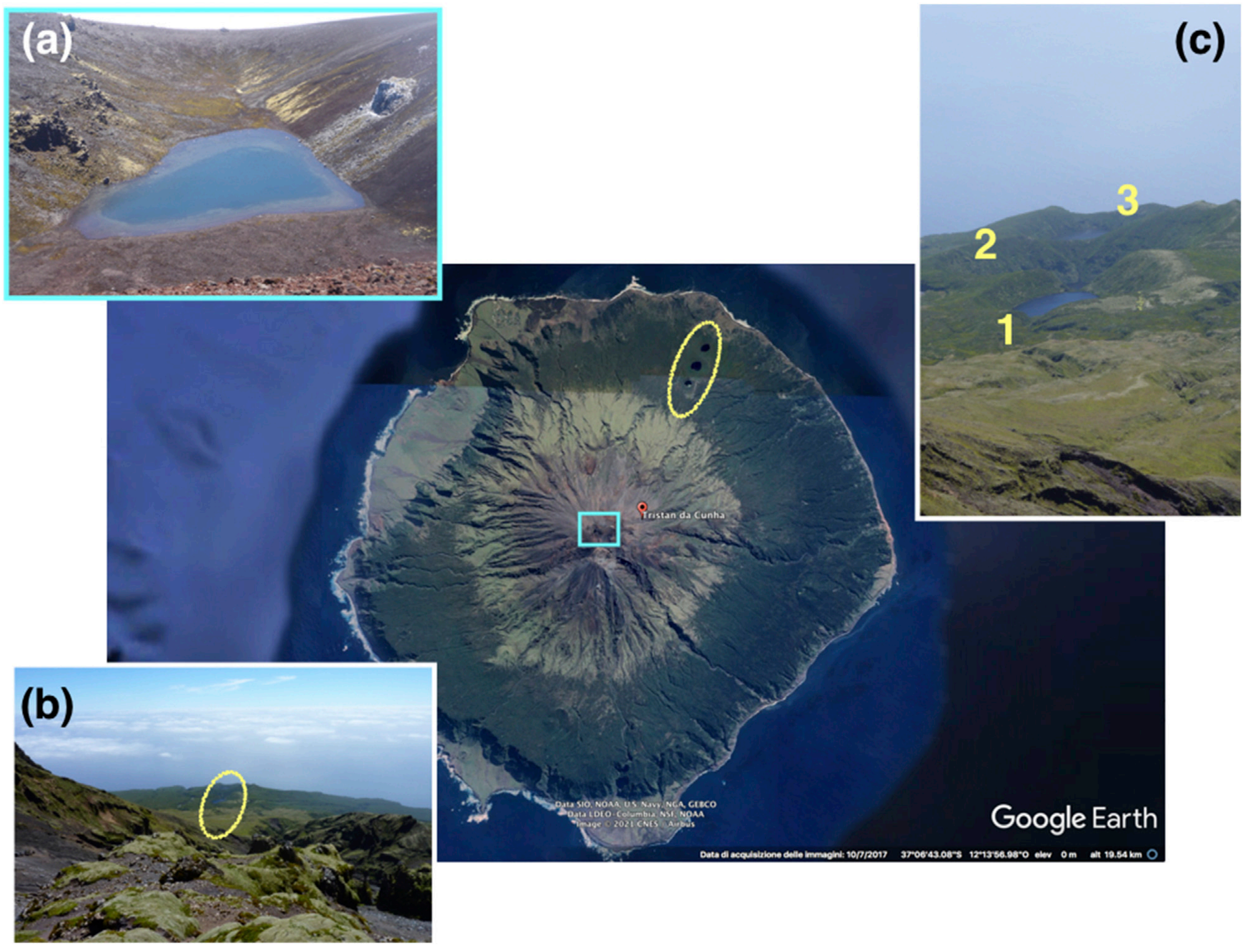

FIGURE 8 | (A) The heart-shaped crater lake of the St. Mary's Peak of Tristan da Cunha, Southern Atlantic Ocean (turquoise square in inset map); **(B)** location of the aligned maars at northern flank of Tristan da Cunha island (yellow ellipse in inset map); **(C)** the three maar lakes, called "the ponds." Note: the yellow patches to the right of "pond 1" are lichens, not sulphur remnants of extinct fumaroles (pictures by A. Hicks).

Southeast of Africa, in the Comores Archipelago, the crater of the Karthala shield volcano was filled by a green lake prior to the 2005 eruption (Pons, 2006) (**Figure 1A**). The lake is ephemeral as the open-conduit volcano is often a heat emitter too high for the lake to sustain. The Dziani Boundouni lake on Mohéli Island (Comores, **Figure 1A**) is a maar lake with, arguably, at least two nested craters. Lake Dziani Dzaha, a shallow (5 m deep) maar lake on a minor island east of Mayotte (Comores, **Figure 1A**) is located only 240 m from the Indian Ocean, and its chemistry is hence affected by seawater. The lake is studied for its microbialites (i.e. sediment aggregates formed by microbial activity) and microbial productivity (Fouilland et al., 2014; Dupuy et al., 2016). Volcanic hazard assessment remains an untouched topic, despite the manifestations of minor CO_2 degassing, probably of volcanic origin (https://www.youtube.com/watch?v=XsgoWl728hM).

All nine "off-shore" volcanic lakes in Africa are poorly studied, and probably mainly fed by meteoric water.

MORPHOMETRIC ANALYSIS

From the 220 volcanic lakes in Africa, 172 are classified as maar lakes, based on their volcanic setting (*see* **section 2**) and morphological aspects (**Table 1**). Whereas approximately 54% of the maars (i.e. craters) in the MaarVLS database by Graettinger (2018) are located at elevations below 750 m a.s.l., about 86% of the African volcanic lakes are located above 800 m a.s.l., despite being predominantly maar lakes (**Figure 9A**). In fact, the maar lakes in Kenya, Tanzania and Uganda are located in volcanic fields in the highlands created by the horst-graben structure of the EAR, in Cameroon in the CVL, and in the central highlands of Madagascar. Crater lakes on the stratovolcanoes Dendi, Wonchi and Zuquala in Ethiopia, Mt Kenya in Kenya and Bisoke and Muhavura in Rwanda are hosted in craters or glacial depressions above 2,800 m a.s.l. Lakes at low elevations (0–300 m a.s.l.) are found on the islands (Nosy Be Island in Madagascar and off-continent islands), near the Atlantic Ocean in Cameroon, or in the Sahara Desert in Libya.

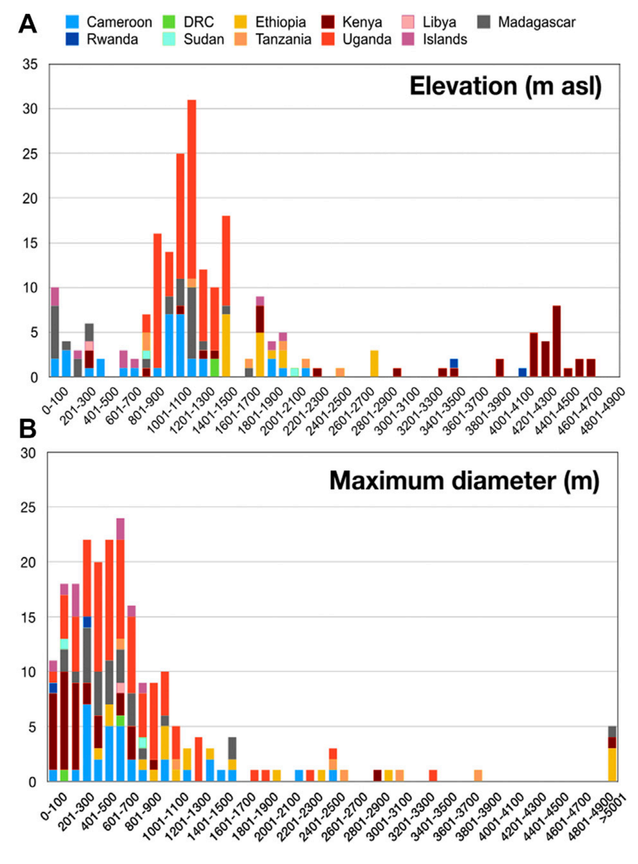

FIGURE 9 | Histograms of parameters for the 220 African volcanic lakes: **(A)** elevation (in m a.s.l.), and **(B)** maximum diameter (in m).

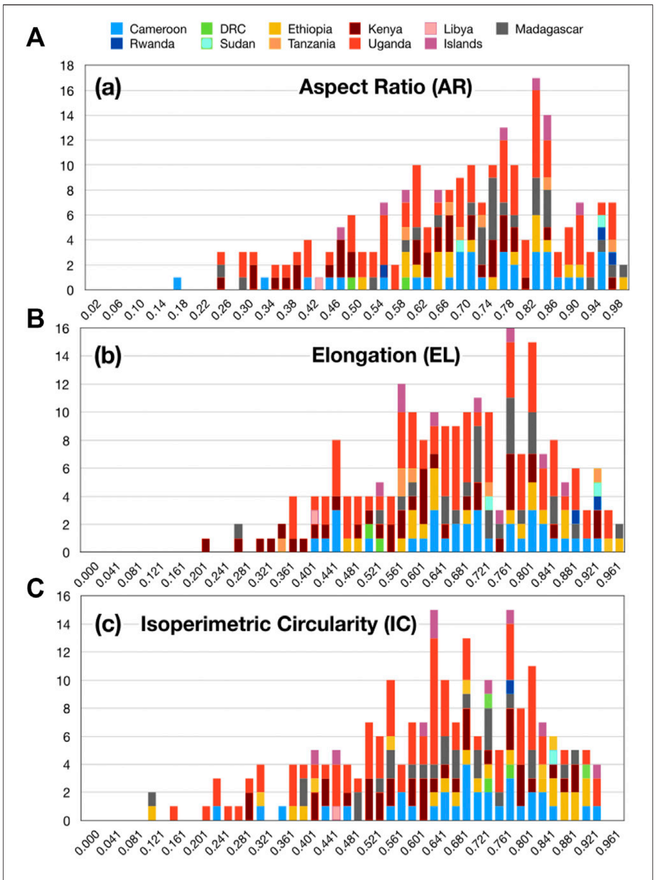

FIGURE 10 | Histograms of morphometric parameters (from Graettinger, 2018) for the 220 African volcanic lakes: **(A)** Aspect Ratio (AR), **(B)** Elongation (EL), and **(C)** Isoperimetric circularity (IC).

Excluding the four caldera lakes and one composite maar (Lake Itasy, Madagascar), the distribution of the maximum diameter of African volcanic lakes peak between 400 and 800 m, similar as for maar lakes worldwide (Graettinger, 2018) (**Figure 9B**). In conclusion, the African volcanic lakes are hence merely maar lakes, but are clearly located at higher elevations, if compared with maars worldwide (Graettinger, 2018).

The average Aspect Ratio (AR, i.e. a measure of the distance from the centre of the lake for minor and major axis) for the African volcanic *lakes* of 0.69 (±0.18 STDEV) is lower than for maar *craters* worldwide (0.81, Graettinger, 2018), also reflected in **Figure 10A** as a more smeared out distribution towards lower AR values. The AR peaks at 0.82–0.86, with a secondary peak at 0.74–0.80 (**Figure 10A**). Only 4% of the AR ratios are above 0.96, whereas 17% are below 0.5. The irregularly shaped Lake Monoun has the lowest AR (0.17), despite being a maar lake. Its river flow-through nature can explain its irregular shape, stressing a dynamic sedimentary regime for Lake Monoun. Indeed, Graettinger, 2018 suggested that maars with anomalous shapes should become a focus for future research to better understand the interaction between local hydrology and its volcanic creation; multiple overlapping maar craters corroborate polygenetic maar formations.

The Elongation (EL, i.e. a measure of the asymmetry of the lake shapes) of African volcanic lakes averages 0.69 (±0.16 STDEV), again lower than the EL values for maar *craters* (0.80 ± 0.12; Graettinger, 2018). 93% of EL values are below 0.92 (versus 85% for maar *craters*); 16% are below 0.5 (versus 5% for maar *craters*; Graettinger, 2018) (**Table 1**). EL peaks at 0.76–0.82 (**Figure 10B**). Although the lakes on the flanks of Mt Kenya weigh in this distribution, caldera and crater lakes do not deviate more from El = 1 than maar lakes do, hence suggesting that maar lakes in Africa appear more elongated with respect to maar craters worldwide. This observation can be explained by a structural control on the morphology of maar lakes and volcanism of the East African Rift system (e.g. Hunt et al., 2020), or more in general, that the maars are located in an extensional rift axis where hydrogeology also plays a role as they are low, longitudinal valleys.

Figure 10C represents a similar distribution of Isoperimetric Circularity (IC, i.e. a measure of the circularity of the lake shape) as for AR and EL. The average IC for African volcanic lakes is 0.66 (±0.18 STDEV), clearly lower than for maar *craters* worldwide (0.9 ± 0.08; Graettinger, 2018). IC values of 0.62–0.64 and 0.76–0.78 are the most common (**Figure 10C**). Contrary to the statistical distribution for maar *craters*, only 6% of volcanic lakes in Africa have an IC value above 0.9 (versus 65% for maar *craters* worldwide), whereas 76% have an IC value below 0.8 (versus 9% for maar *craters* worldwide; Graettinger, 2018). For maar *craters*, IC values below 0.9 were explained to reflect a compound shape. Caution is needed to avoid over interpretation of the IC trends for African volcanic *lakes*, in the light of Graettinger, 2018 correct hypothesis for maar *craters*: *1*) lakes do not necessarily fill up entire circular-shaped craters, but can present with a more exotic, less circular morphology, and *2*) islands and peninsula in the larger lakes, considered in the calculation of A and p (**Eq. 3**) of the volcanic lakes, can drastically decrease the IC values. Nevertheless, the lower IC values resulting from (2) can be an additional argument in favor of polygenetic phreatomagmatic volcanism leading to irregular craters and lakes.

CONCEPTUAL MODEL: WHY ARE MAAR LAKES SO DOMINANT IN AFRICA?

Besides Lakes Nyos and Monoun, none of the African volcanic lakes are (well) studied regarding volcanic hazard assessment. Pioneering work on paleo-, bio- and physical limnology and hydroclimatology for lakes in Cameroon, Uganda, Kenya, Tanzania and Ethiopia (Kling, 1988; Eggermont et al., 2006; Kebede et al., 2009; Lemma, 2009; Russell et al., 2009; Giresse and Makaya-Mvoubou, 2010; Ryves et al., 2011; Garcin et al., 2012; Loomis et al., 2012; Garcin et al., 2014; Lebamba et al., 2016; De Crop and Verschuren, 2019) should guide volcanologists to shed light on the many poorly studied lakes in Africa (predominantly quoted "5" in VOLADA_Africa 2.0, **Table 1**) with the scope to better assess future natural hazards.

Besides the 26 glacial volcanic lakes of Mt Kenya (Loomis et al., 2012), about 89% (172) of volcanic lakes reported for Africa are maar lakes (**Table 1**). Africa does not host any peak activity lakes (i.e. acidic crater lakes overlying degassing magmatic-hydrothermal systems, often subjected to phreatic and phreatomagmatic eruptions; Rouwet, 2021), peculiar for such a large continent with active volcanoes (Global Volcanism Program, 2013). However, the continent does not manifest "classical" arc-type volcanism, but evidently hosts intraplate polygenetic volcanoes with a different chemical affinity than arc volcanoes. Hydrothermal activity is abundant, but is mainly related to the gradual break-up of the thick continental crust (e.g. EAR, **Figure 11**), and to mafic magmas.

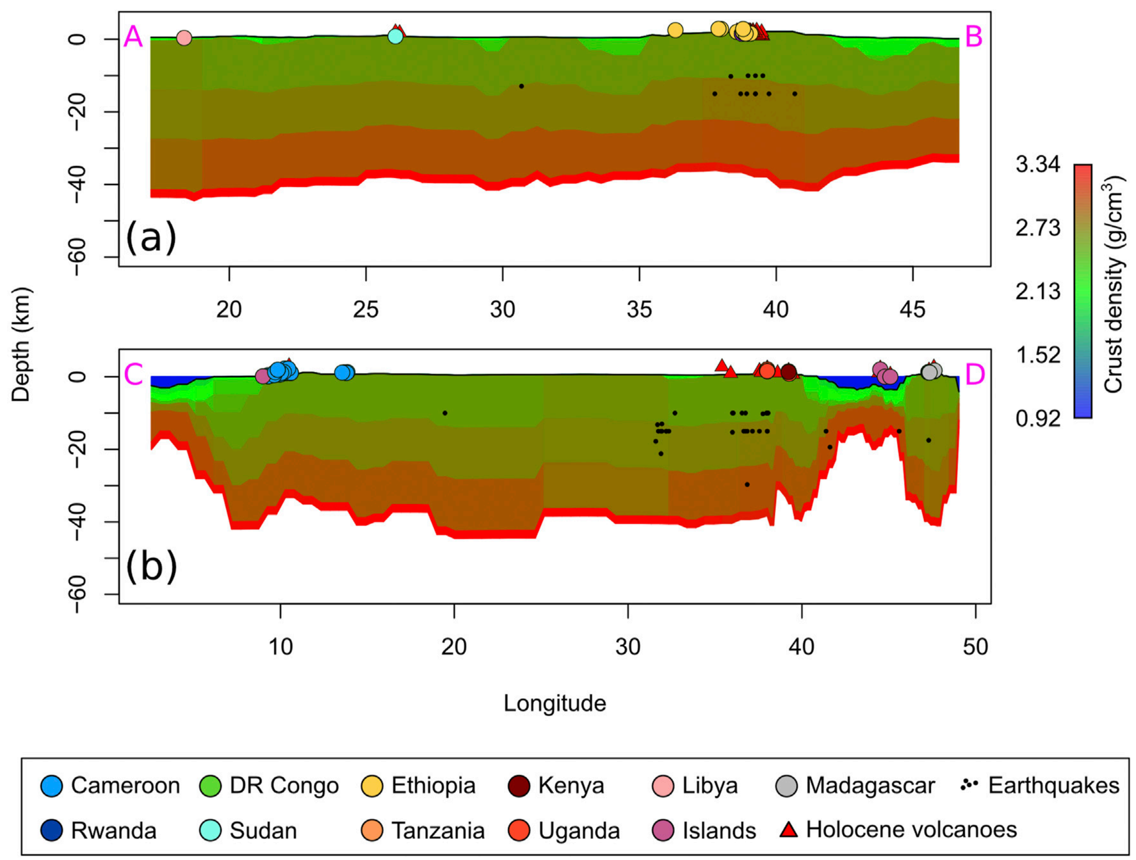

FIGURE 11 | Conceptual model to explain the abundant maar volcanism of the EAR and CVL, through a vertical section of the first 40–50 km through the Earth's crust (Laske et al., 2013). The transects A-B and C-D are traced in **Figure 1**. Holocene active volcanoes are exported from the Global Volcanism Program-Smithsonian database (https://volcano.si.edu/).

Stratovolcanoes or (dome) complex volcanoes with well-developed hydrothermal systems that provide the prototype settings to develop crater lakes on volcano summits (wet volcanoes; Caudron et al., 2015; Rouwet et al., 2015b), are relatively scarce in Africa. The EAR volcanism is MORB- or OIB-type leading to predominantly basaltic (Mt Cameroon; Mbassa et al., 2012; Kervyn et al., 2014; Adams et al., 2015; Nyamulagira, Nyiragongo; Pouclet et al., 2016; Karthala, outside the EAR; Class et al., 2009; Pelleter et al., 2014), or sporadically carbonatitic volcanism (Oldoinyo Lengai; Kervyn et al., 2014; Keller and Zaitsev, 2012; Weidendorfer et al., 2017). Despite the tropical climate and abundant rainfall in subsaharan Africa, insufficient constraints are met to sustain crater lake presence at the active volcanoes (Pasternack and Varekamp, 1997), for example: *1*) a too high heat flux from open-conduit volcanoes (i.e., lava lakes instead of "water lakes" in most extreme cases, e.g. Nyiragonogo, Nyamulagira, and Erta Ale; Giggenbach and Le Guern, 1976), and *2*) a too high permeability of the volcanic edifice, flushing out meteoric water from the summit areas of volcanoes. Instead, aquifers arguably accumulate at the base of volcanoes, or in rift depressions, hence creating an ideal hydrogeological architecture for magma-water interaction to take place at lower elevations (**Figure 11**), resulting in phreatomagmatic eruptions and consequent maar formation, a common phenomenon observed in monogenetic volcanic fields (e.g. Cas et al., 2017; Kereszturi et al., 2017). The many maar fields in Africa (e.g. Uganda, in the EAR, and Cameroon, in the CVL) probably reflect this large-scale and tectonically driven process. In fact, active seismicity occurs along the EAR (International Seismological Centre, 2020), as well as Holocene active volcanism does (Global Volcanism Program, 2013) (**Figures 1, 11**). Unsurprisingly, seismicity, volcanism and volcanic lakes occur where the Earth crusts thins due to rifting, as shown in the two transects A-B and C-D in **Figures 11A,B**, respectively. The CVL is often interpreted as resulting from failed rifting following continental break up starting 120 Ma ago (Fitton, 1983; Aka et al., 2004); volcanism in Cameroon and the southern islands hence occur along this aulacogen (**Figure 11A**).

Within this maar-rich setting, combined with regional scale CO_2-rich degassing along the EAR and CVL, the deepest lakes in Africa might be able to store dissolved CO_2 in their bottom waters. The absence of a high gradient in yearly atmospheric temperature, and thus lake surface water temperature, favors meromixsy (e.g. Lake Nyos); instead, possible geothermal heating in deep rift lakes (e.g. Lake Kyaninga) inhibits a stable thermal stratification. The latter process provides a hypothesis for the observation that no other maar lake along the EAR or CVL has bursted in a fatal way like Lake Monoun and Lake Nyos did in 1984 and 1986, respectively. Moreover, possible diurnal cycles in the stratification, especially in the epilimnion of high-altitude lakes in Uganda, Kenya, Ethiopia, Tanzania and Cameroon, however, favors daily partial mixing and, hence, possible degassing if the lakes are fed by gas-rich fluids from below. Needless to say that further research in physical limnology, hydrogeology and fluid geochemistry of single lakes is highly recommendable in order to better assess future volcanic hazard for the 172 African maar lakes.

FINAL REMARKS AND STRATEGIES FOR FUTURE RESEARCH

VOLADA_Africa 2.0 compiles arguably the complete number of volcanic lakes on the African continent (220), Madagascar and the minor islands. Volcanic lakes are pin-pointed, country by country, through decimal coordinates, made available to the community (https://vhub.org/resources/). All lakes are classified for their genetic origin (Christenson et al., 2015), and physical and chemical characteristics (Rouwet et al., 2014, and references therein). The classification results as follows:

(1) 18 lakes are crater lakes (Manengouba Lakes, Cameroon; crater lakes of Zuquala, Dendi and Wonchi volcanoes, Ethiopia; Rutundu and Alice on Mt Kenya, Kenya; Waw an Namus in Libya; Mt Bisoke's and Mt Muhavura crater lakes, Rwanda; Deriba crater lakes, Sudan; Empakaai, Magadi and Ngozi crater lakes in Tanzania; crater lakes on the islands of Annobon, Bioko, Tristan da Cunha and Karthala);
(2) 4 are caldera lakes (3 in the O'a Caldera, Ethiopia; Lake Chala in Tanzania);
(3) 26 are lakes filling glacial depressions on the flanks of Mt Kenya (Kenya);
(4) The remaining 172 volcanic lakes are maar/tuff cone lakes.

Africa does not host peak-activity or high-activity lakes in active volcano craters. The renowned "killer lakes" Nyos and Monoun are "5b2-type" lakes (i.e. gas storing Nyos-type lake); Lake Nyungu and Lake Kyaninga, two of the 81 maar lakes in Uganda, are suspected to be "Nyos-type lakes." Arguably all lake waters have a purely meteoric origin, that attained a chemical equilibrium upon water-rock interaction with the host rock of the lake basin (i.e. rock-dominated lakes), and evaporation, in more or less extent. We proposed a conceptual model on why Africa provides the ideal tectonic and volcanic settings for maar lakes to form, and why peak activity crater lakes, "windows" into "wet volcanoes" are absent, in spite of the often ideal climatic conditions for such lakes to form. The dominance of intraplate volcanism and the absence of arc-type volcanism appear to be key factors.

The uniqueness to accomplish the necessary conditions for a gas burst to occur has been extensively studied during the past 30+ years. As we presumably know why the two fatal gas bursts *did* occur, the question for the remaining 172 African maar lakes seems to be "why do gas bursts *not* occur?" (by assuming they did not), as climatic, limnological and volcanic constraints are very similar than those for the Cameroonian "killer" lakes. Non-volcanological explanations that haze our insights into possible other "Nyos-type" events in the past lie in the facts that *1*) written history is reported only since the late 19th century for most of the African continent, and *2*) volcanic lakes are often located in remote and poorly inhabited regions. The recurrence time of geological phenomena is longer (e.g. 100–10,000's of years for dyke intrusions, maar formation, and "Nyos-type" gas bursts), and hence not synchronized with written history. Nevertheless, clues on suspicious "Nyos-type" behavior could be found in the study of oral traditions and legends that trace further back in the past. Future historiographical research should hence aim at explaining if "only" two lethal gas bursts occurred (Monoun-1984, Nyos-1986), as reported in the documented history (Westerman, 2013). Moreover, the database on volcanic lakes in Africa presented here can be a useful resource to apply to other continents as a future aim of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) Commission on Volcanic Lakes.

AUTHOR CONTRIBUTIONS

DR Development idea, MS writing, DB compilation, elaboration data KN Development idea, MS writing GT MS writing, DB compilation, elaboration data SC MS writing, field work, elaboration data I MS writing, field work.

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