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Supplementary material: A novel approach to volcano surveillance using gas geochemistry

Yves Moussallam *, [a], [b], **Clive Oppenheimer** [c] and **Bruno Scaillet** [d]

[a] Lamont-Doherty Earth Observatory, Columbia University, New York, USA

[b] Department of Earth and Planetary Sciences, American Museum of Natural History, New York, USA

[c] Department of Geography, University of Cambridge, Downing Place, Cambridge CB2 3EN, UK

[d] ISTO, 7327 Université d'Orléans-CNRS-BRGM, 1A rue de la Férollerie, 45071 Orléans cedex 2, France

E-mails: yves.moussallam@ldeo.columbia.edu (Y. Moussallam), co200@cam.ac.uk (C. Oppenheimer), bscaille@cnrs-orleans.fr (B. Scaillet)

* Corresponding author.

Supplementary Table S1. Literature compilation of volcanic gas composition measurements

Volcano	Measuring time	Reference	Original gas composition (mol %)								
			H2O	CO_2	SO_2	HCl	HF	CO	H_2S	H_2	OCS
Erta 'Ale	15/01/2011	(Zelenski et al., 2013)	62.6	20.7	10.9	0.47	0.34	0.31	0.54	0.68	
	23/01/1974	(Giggenbach and Le Guern, 1976)	78.2	11.1	6.4	0.42			0.87	1.6	
	29/01/1974	(Guern et al., 1979)	71.3	19.4	4.9				0.82	2.09	
	28/01/1974	(Guern et al., 1979)	70.4	18.4	6.7				0.38	2.36	
	23/01/1974	(Guern et al., 1979)	80.7	9.5	5.9					1.61	
	1974	(Giggenbach, 1996)	79.4	9.9	7.8	0.7		0.27		0.75	
Surtsey	1965	(Gerlach, 1980) orig. (Sigvaldason and Elísson, 1968)	90.6	5.9	2.6	0.42			0.49		
Ardoukoba	1978	(Gerlach, 1981) orig. (Allard, 1979)	80.0	3.9	14.4				1.71		
Mauna Loa	1987	(Greenland, 1987)	70.0	4.6	24.7	0.02	0.03		0.38		
Usu	1979	(Symonds et al., 1994)	96.4	2.7	0.2	0.16	0.03		0.54		
	?	(Giggenbach, 1996)	99.3	0.4	0	0.03	0.01	0	0.02	0.2	
Satsuma Iwo Jima	1957	(Symonds et al., 1996)	99.5	0.4	0	0.05	0.02		0		
	?	(Giggenbach, 1996)	98.0	1.2	0	0.05	0.02	0	0	0.63	
	1990	(Gerlach, 2004)orig.(Shinohara et al., 1993)	97.5	0.3	0.9	0.68	0.03	0	0.07	0.47	
	1993	(Goff and McMurtry, 2000)	97.8	0.3	0.9	0.39	0.09		0.03	0.45	
	?	(Giggenbach, 1996)	97.3	0.5	0.8	0.53	0.03	0	0.16	0.61	
Unzen	1992	(Ohba et al., 1994)	95.5	2.7	0.7	0.26		0.03		0.78	
Merapi	1979	(Gerlach, 2004) orig. (Le Guern et al., 1982)	89.9	7.2	1.2	0.6	0.04		1.13		
		(Allard, 1983), (Le Guern et al., 1982)	92.9	4.8	0.6	0.2	0.01		0.56	0.73	
	1994	(Giggenbach et al., 2001)	88.7	5.6	1	0.61	0	0.02	0.13	0.5	
Krakatau		(Allard, 1983)	99.0	0.2	0.6			0	0	0.02	
Ngauruhoe	?	(Giggenbach, 1996)	96.0	1.6	1	0.25		0	0.68	0.14	
Kudryavy	1992	(Taran et al., 1995)	94.4	1.8	1.8	0.46	0.03	0	0.18	1.18	
	1995	(Fischer et al., 1998)	95.3	1.2	2.1	0.74	0.1	0	0.39	0.78	
	1991	(Taran et al., 1995)	94.7	2.4	1.6	0.75	0.08		0.51		
Kluichevskoi	?	(Giggenbach, 1996)	97.7	0.1	0.1	1.42	0.25		0	0.59	
Tolbachik	1976	(Taran et al., 1987)	98.0	0	0.1	1.06	0.28	0	0.13	0.55	
Poás	1981	(Symonds et al., 1994)	96.7	1	1.5	0.75	0.09		0.01		
	1981	(Rowe et al., 1992)	95.0	1.4	2.8	0.38	0.02	0.01		0.9	
Momotombo	1985	(Menyailov et al., 1986)	92.9	4.6	0.9	0.59	0.02		0.98		
	1982	(Giggenbach, 1996)	95.1	2.4	0.7	0.35	0.03	0.03	0.49	0.87	
	2002	(Elkins et al., 2006)	96.3	2.5	0.2	0.53	0.04	0.01		0.35	
Galeras	1992	(Giggenbach, 1996)	91.8	6	0.8	0.71	0.06		0.57		
	1991	(Giggenbach, 1996)	91.5	6	0.8	0.72	0.06	0.01	0.57	0.29	
Mt. St. Helens	1980	(Gerlach and Casadevall, 1986)	92.4	7	0.2	-	-		0.36		
	?	(Symonds et al., 1994)	98.9	0.9	0.3	0.15	0.03	0		0.4	
Augustine	?	(Symonds et al., 1990)	84.8	2.3	7	1.01	0.09	0.02		0.54	
Soufrière Hills	1996	(Hammouya et al., 1998)	95.9	2	0.4	1.72	-		0.03		
Vulcano	?	(Giggenbach, 1996)	86.1	11.9	0.7	0.45	0.1	0.01	0.48	0.15	
	1991	(Giggenbach and Matsuo, 1991)	85.8	12.4	0.7	0.43	0.12	0.01	0.53	0.2	
Tolbachik	2013	(Chaplygin et al., 2016)	95.5	0.5	2	1.18	0.34	0		0.39	
Benbow*	2008	(Allard et al., 2016a; Allard et al., 2016b)	96.2	2.2	1.1	0.35	0.19	0			
	2007		93.7	2.7	2.7	0.62	0.26				
	2007		96.5	1.6	1.5	0.3	0.13		0.02		
Gorely	2011	(Aiuppa et al., 2012)	93.5	2.6	2.2	1.1	0.3			0.2	
Etna	03-sept-09	(Aiuppa et al., 2011)	82.5	9.1	8.2				0.07	0.15	
	03-sept-09		90.1	5.4	4.5				0.02	0.01	
	04-sept-09		86.1	6.1	7.6				0.08	0.13	
	04-sept-09		94.0	2.8	3.1				0.01	0.01	
	05-sept-09		98.1	1	0.9				0	0.01	
	09-nov-09		52.8	34.2	12.7				0.13	0.22	
Sabancaya	2015	(Moussallam et al., 2017b)	73.4	15.2	10.1				1.15	0.15	
Isluga	2016	(Schipper et al., 2017)	85.9	6	6.9				1.11	0.14	
Lastarria	2015	(Schipper et al., 2017)	78.2	14	5.9				1.78	0.08	
El Misti	2015	(Moussallam et al., 2017a)	89.0	7.5	2.8				0.64	0.03	
Nevados de Chillán	2015	(Moussallam et al., 2018)	98.4	1	0.1				0.01	0.5	
Bromo	2014	(Aiuppa et al., 2015)	94.8	3.8	0.9				0.24	0.21	
Nyiragongo	2005	(Sawyer et al., 2008)	70.5	23.7	4.6	0.26	0.11	0.86			0.0023
Erebus	2010-2011	(Moussallam et al., 2012)	47.8	44	1.1	0.46	1.16	3.3	0.55	1.58	0.0088
Kīlauea	2013	(Oppenheimer et al., 2018)	92.2	4	3.5	0.06	0.04	0.12			0.0003
			89.3	5.9	4.6	0.06	0.05	0.1			0.0007
Dukono	2014	(Bani et al., 2018)	97.2	0.8	1.6				0.06	0.3	
Ibu	2015	(Bani et al., 2021)	99.3	0.6	0				0.03	0.08	
Gamkonora	2018	(Saing et al., 2020)	94.7	3.9	0.7				0.4	0.2	
Gaua/Mt Garet	2018	(Lages et al., 2020)	95.9	1.8	2				0.26	0.06	

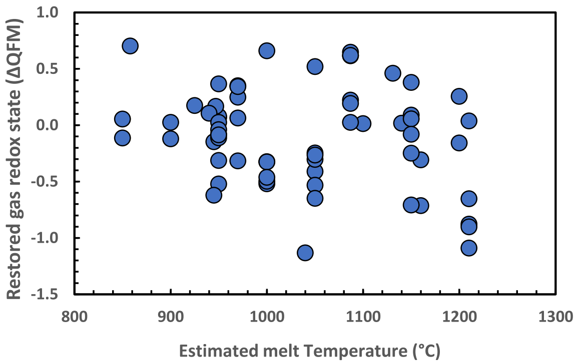
Supplementary Table S2. Equilibrium temperature and initial oxidation state of high temperature volcanic gases from global database, compared to estimated magma temperature and restored oxidation state at magmatic temperature

Volcano	Measuring time	Reference	Gas collection T or AET (°C)	ΔQFM gas	Magma type	Estimated Melt T(°C)	Method for melt temperature estimation	Reference	ΔQFM of restored gas at magmatic T
Erta 'Ale	15/01/2011	(Zelenski et al., 2013)	1084	0.1	basalt	1160	Olivine-liquid geothermometer	(de Moor et al., 2013)	**-0.3**
	23/01/1974	(Giggenbach and Le Guern, 1976)	1135	-0.5	basalt	1210	Highest direct measurement	(Guern et al., 1979)	**-0.9**
	29/01/1974	(Guern et al., 1979)	1100	-0.8	basalt	1210			**-1.1**
	28/01/1974	(Guern et al., 1979)	1210	-0.9	basalt	1210			**-0.9**
	23/01/1974	(Guern et al., 1979)	1135	-0.5	basalt	1210			**-0.7**
	1974	(Giggenbach, 1996)	1131	0.3	basalt	1210			**0.0**
Surtsey	1965	(Gerlach, 1980) orig. (Sigvaldason and Elísson, 1968)	1125	-0.7	Alkaline basalt	1160	lava temperatures measured in 1965	(Sigvaldason and Elísson, 1968)	**-0.7**
Ardoukoba	1978	(Gerlach, 1981) orig. (Allard, 1979)	1070	-0.4	Tholeiitic basalt	1150	Arbitrary, based on basaltic composition		**-0.7**
Mauna Loa	1987	(Greenland, 1987)	1130	-0.1	Tholeiitic basalt	1140	Measured	(Lipman and Banks, 1987)	**0.0**
Usu	1979	(Symonds et al., 1994)	676	0.9	Dacite	950	Estimated from magnetite geothermometry (for the 1977 to 2000 pumice)	(Tomiya and Takahashi, 2005)	**-0.5**
	?	(Giggenbach, 1996)	690	1.4	Dacite	950			**0.1**
Satsuma Iwo Jima	1957	(Symonds et al., 1996)	791	1.2	Rhyolite	970	T used in model	(Kazahaya et al., 2002)	**0.3**
	?	(Giggenbach, 1996)	800	0.4	Rhyolite	970			**-0.3**
	1990	(Gerlach, 2004)orig.(Shinohara et al., 1993)	877	0.7	Rhyolite	970			**0.2**
	1993	(Goff and McMurtry, 2000)	885	0.8	Rhyolite	970			**0.3**
	?	(Giggenbach, 1996)	880	0.5	Rhyolite	970			**0.1**
Unzen	1992	(Ohba et al., 1994)	818	0.2	Dacite	900	Post-mixing temperature from oxides and in agreement with experiments	(Venezky and Rutherford, 1999)	**-0.1**
Merapi	1979	(Gerlach, 2004) orig. (Le Guern et al., 1982)	915	-0.3	Andesite	950	Amphibole geothermometer on 2010 product	(Costa et al., 2013)	**-0.3**
		(Allard, 1983), (Le Guern et al., 1982)	915	0.3	Andesite	950			**-0.1**
	1994	(Giggenbach et al., 2001)	803	0.6	Andesite	950			**0.1**
Krakatau		(Allard, 1983)	687	3.3	Andesite	1131	Geothermometry based on clinopyroxenes from 1883 to 1981	(Dahren et al., 2012)	**0.5**
Ngauruhoe	?	(Giggenbach, 1996)	640	1.7	Andesite	1000	Average temperature used to model plagioclase An composition	(Coote and Shane, 2016)	**-0.3**
Kudryavy	1992	(Taran et al., 1995)	940	-0.1	Basaltic andesite	1050	Arbitrary, based on basaltic andesite composition		**-0.4**
	1995	(Fischer et al., 1998)	920	0.3	Basaltic andesite	1050			**-0.3**
	1991	(Taran et al., 1995)	910	0.0	Basaltic andesite	1050			**-0.5**
Kluichevskoi	?	(Giggenbach, 1996)	1100	0.6	Basalt	1200	Average of estimated melt inclusion quench temperature	(Mironov and Portnyagin, 2011)	**0.3**
Tolbachik	1976	(Taran et al., 1987)	1020	0.6	Basalt	1150	Plagioclase crystallisation temperature	(Romanchev and Flerov, 1980)	**0.1**
Poás	1981	(Symonds et al., 1994)	1045	0.5	Basaltic andesite	1050	Average temperature from pyroxene geothermometry	(Cigolini et al., 1991)	**0.5**
	1981	(Rowe et al., 1992)	940	0.1	Basaltic andesite	1050			**-0.2**

(continued on next page)

Supplementary Table S2. (continued)

Kluichevskoi	?	(Giggenbach, 1996)	1100	0.6	Basalt	1200	Average of estimated melt inclusion quench temperature	(Mironov and Portnyagin, 2011)	**0.3**
Tolbachik	1976	(Taran et al., 1987)	1020	0.6	Basalt	1150	Plagioclase crystallisation temperature	(Romanchev and Flerov, 1980)	**0.1**
Poás	1981	(Symonds et al., 1994)	1045	0.5	Basaltic andesite	1050	Average temperature from pyroxene geothermometry	(Cigolini et al., 1991)	**0.5**
	1981	(Rowe et al., 1992)	940	0.1	Basaltic andesite	1050			**-0.2**
Momotombo	1985	(Menyailov et al., 1986)	860	-0.1	Basalt	1000	Highest temperature from coexisting Fe-Ti oxide	(Benhamou et al., 1988)	**-0.5**
	1982	(Giggenbach, 1996)	844	0.2	Basalt	1000			**-0.5**
	2002	(Elkins et al., 2006)	747	0.9	Basalt	1000			**-0.3**
Galeras	1992	(Giggenbach, 1996)	642	1.5	Andesite	945	Highest temperature from coexisting Fe-Ti oxide	(Calvache V and Williams, 1997)	**-0.1**
	1991	(Giggenbach, 1996)	642	1.0	Andesite	945			**-0.6**
Mt. St. Helens	1980	(Gerlach and Casadevall, 1986)	802	0.1	Dacite	850	Fe–Ti temperature	(Pallister et al., 2008)	**-0.1**
	?	(Symonds et al., 1994)	710	0.8	Dacite	850			**0.1**
Augustine	?	(Symonds et al., 1990)	870	0.5	Andesite	947	Highest temperature from Fe-Ti oxide compositions	(Roman et al., 2006)	**0.2**
Soufrière Hills	1996	(Hammouya et al., 1998)	720	1.5	Andesite	858	Pyroxene geothermometry	(Murphy et al., 2000)	**0.7**
Vulcano	?	(Giggenbach, 1996)	620	1.5	Rhyolite	1000	Feldspar geothermometry for rhyolite	(Masotta and Trigila, 2008)	**-0.5**
	1991	(Giggenbach and Matsuo, 1991)	858	1.3	Rhyolite	1000			**0.7**
Tolbachik	2013	(Chaplygin et al., 2016)	1030	0.9	Basalt	1150	Plagioclase crystallisation temperature	(Romanchev and Flerov, 1980)	**0.4**
Benbow*	2008	(Allard et al., 2016a; Allard et al., 2016b)	769	1.8	basalt	1150	MELT calculations	(Allard et al., 2016)	**0.1**
	2007								**0.0**
	2007								**0.0**
Gorely	2011	(Aiuppa et al., 2012)	810	1.4	basalt	1100	Pyroxene crystallisation temperature from modelling	(Chashchin et al., 2011)	**0.0**
Etna	03-sept-09	(Aiuppa et al., 2011)	813	1.6	basalt	1087	Value used in model	(Bonaccorso et al., 2011)	**0.2**
	03-sept-09		529	4.0	basalt	1087			**0.6**
	04-sept-09		781	1.7	basalt	1087			**0.2**
	04-sept-09		532	4.0	basalt	1087			**0.6**
	05-sept-09		531	4.0	basalt	1087			**0.6**
	09-nov-09		907	0.9	basalt	1087			**0.0**
Sabancaya	2015	(Moussallam et al., 2017b)	713	1.4	Andesite to Dacite	940	magmas expelled during the 1990–1998 crisis	(Gerbe and Thouret, 2004)	**0.1**
Isluga	2016	(Schipper et al., 2017)	678	1.6	Andesite?	950	Arbitrary, based on andesite composition		**0.0**
Lastarria	2015	(Schipper et al., 2017)	607	2.0	Andesite to Dacite	950	mean value of various geothermother (mostly pyroxene pairs)	(Stechern et al., 2017)	**-0.1**
El Misti	2015	(Moussallam et al., 2017a)	531	2.8	Andesite	925	Mean temperature of the Andesite constrained by phase equilibria	(Tepley et al., 2013)	**0.2**
Nevados de Chillán	2015	(Moussallam et al., 2018)	839	0.7	Andesite?	950	Arbitrary, based on andesite composition		**0.0**
Bromo	2014	(Aiuppa et al., 2015)	696	1.4	Andesite	950	Arbitrary, based on andesite composition		**-0.1**
Nyiragongo	2005	(Sawyer et al., 2008)	1140	0.1	basanite	1200	Arbitrary, based on basaltic composition		**-0.2**
Erebus	2010-2011	(Moussallam et al., 2012)	988	-0.9	Phonolite	1040	Based on maximum gas equilibrium temperature		**-1.1**
Kīlauea	2013	(Oppenheimer et al., 2018)	1099	0.2	basalt	1150	Mean temperature from olivine-hosted melt inclusions	(Sides et al., 2014)	**-0.1**
			1008	0.4	basalt	1150			**-0.2**
Dukono	2014	(Bani et al., 2018)	826	1.1	Andesite	950	Arbitrary, based on andesite composition		**0.4**
Ibu	2015	(Bani et al., 2021)	565	2.2	Dacite	900	Arbitrary, based on Dacite composition		**0.0**
Gamkonora	2018	(Saing et al., 2020)	664	1.4	Andesite to Basaltic Andesite	1050	Arbitrary, based on basaltic andesite composition		**-0.7**
Gaua/Mt Garet	2018	(Lages et al., 2020)	594	2.4	Basaltic andesite	1050	Arbitrary, based on basaltic andesite composition		**-0.3**



Supplementary Figure S1. Restored oxidation state of volcanic gases at magmatic temperature from global database (presented in Table S1 and Figure S1) expressed as deviation from the QFM buffer and compared to magmatic temperature.

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