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Mineralogy of the Laetolil Footprint Tuff: A comparison with possible volcanic sources from the Crater Highlands and Gregory Rift

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A B S T R A C T

Sadiman volcano in northern Tanzania was postulated as a source of the Upper Laetolil Tuff 7 renowned for its 3.66 Ma old footprints of *Australopithecus afarensis* as both localities show similarities in terms of their mineralogy. Despite this widely accepted view, Laetoli and Sadiman differ in some key features, particularly in the absence of melilite at Sadiman, and in their magnetite composition. Magnetite from these localities shows significant differences in Mg, Al and Ti contents. Compositions of major, minor and accessory minerals and the occurrence of carbonate–silicate melt inclusions in magnetite from Laetoli indicate their formation from a fractionated carbonate- and melilite-bearing nephelinitic melt. This differs from the melt from which the Sadiman rocks formed. We propose that the nephelinitic Mosonik volcano, located to the north-east from Laetoli, could be a potential source for the Upper Laetolil Footprint Tuff 7.

1. Introduction

Pliocene-Pleistocene volcanic rocks in East Africa are very important for the preservation of hominid and faunal remains at several sites including the famous localities Olduvai Gorge and Laetoli (Fig. 1) (e.g., Hay, 1976; Harrison, 2011). The latter is also an important site where footprints of animals and hominids are well preserved (Leakey and Harris, 1987). Much work has been done to study the tuffs and lavas occurring at Olduvai and Laetoli with the purpose of reconstructing a correlation between tephra deposits and their volcanic sources within the Crater Highland area (McHenry, 2004, 2005; McHenry et al., 2008). In this respect, it is important to know in detail the assemblage(s) of primary minerals and their compositions, to obtain such a correlation.

The Laetoli area is well known for the trails of 3.66 Ma old *Australopithecus afarensis* footprints observed in so-called Footprint Tuff or, more correctly, Upper Laetolil Tuff 7 (e.g., Hay, 1978, 1987; Agnew and Demas, 1998; Deino, 2011). Preservation of the footprints has been explained by the rapid cementation of carbonatite (natrocarbonatite) and melilitite ashes erupted from nearby Sadiman (also known as Satiman) volcano (Fig. 1) (Hay, 1978, 1986, 1987). This conclusion was based on Laetolil tuff mineralogy (particularly from the Upper Laetolil beds) and depositional features including drainage directions within the Laetoli area, and this view is accepted in modern publications (Su and Harrison, 2015 and references herein).

Recent studies of the Laetolil tuffs, including the Footprint Tuff, and lavas and tuffs from the Sadiman volcano provide new information about the mineralogy of volcanic rocks from these localities, which is important for interpreting the relationships between them. Barker and Milliken (2008) suggested that carbonatite (or natrocarbonatite) ash was not deposited at the time of the Footprint Tuff formation; instead a crystal-vitric melilite nephelinite ash was a major component within the original volcanic deposits. The presence of fresh, unaltered melilite and nepheline in the

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Fig. 1. Volcanoes in the Crater Highlands area and the Gregory rift in northern Tanzania. Image data: shaded and coloured SRTM elevation model (February 2000), view size: 100 × 100 km. Image courtesy NASA/JPL/NGA. Africa image: NASA "blue marble" true-colour image (February 2002). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Footprint Tuff was confirmed by McHenry (2011) in her detailed investigation of the Laetolil tuff mineralogy. The source of the Laetolil volcanic deposits was considered to be "… Satiman or a satellite vent from Satiman now covered by younger eruptions from Lemagurut." (Mollel et al., 2011, p. 117). At the same time, on the basis of the mineralogy and geochemistry of volcanic rocks currently exposed at Sadiman, Zaitsev et al. (2011, 2012) suggested that there is no direct evidence for a link between the Footprint Tuff and the volcano.

Although the Footprint tuff texture, structure and general mineralogy has been described by Hay (1978, 1987) and mineral compositions have been given by McHenry (2011), there is only one publication that gives mineralogical information for the tuff from Locality 8, where the hominin footprint trail occurs (Barker and Milliken, 2008) – and this publication only reports calcite.

In addition to the mineralogical and geochemical characteristics of these rocks important information about relationships and origin can also be acquired by the investigation of various types of inclusions which are common in some minerals. Mineralogical studies of both plutonic and volcanic ultramafic and alkaline rocks, as well as associated carbonatites, revealed a number of silicate and oxide minerals that often host solid, melt and fluid inclusions with water-soluble and alkali-rich phases (e.g., Kogarko et al., 1991; Zaitsev, 2010; Sharygin et al., 2011, 2012; Zaitsev et al., 2013; Chen et al., 2013). Unlike silicates, oxide minerals such as perovskite, magnetite, calzirtite, and ilmenite are more resistant to intensive hydrothermal alteration and weathering, and can help preserve inclusions with ephemeral phases (water soluble alkali carbonates, chlorides and sulphates). The study of inclusions provides valuable information that can be used to estimate the compositions of primary, evolved melts and P–T-conditions at the formation of these rocks and minerals.

Magnetite and perovskite are typically accessory and sometimes minor minerals in Pliocene tuffs preserved in the Laetoli area of northern Tanzania (Hay, 1978; McHenry, 2011). Magnetite from volcanic rocks associated with the saline-alkaline basins of the East African Rift, has been described as one of the first minerals to alter (McHenry, 2005; McHenry et al., 2011), but it is a well preserved mineral at Laetoli. In this paper we present the results of a new mineralogical study of the Footprint Tuff, including the composition of melt inclusions in magnetite, and discuss its relationship to Sadiman volcano.

2. Material and methods

The three studied Footprint Tuff 7 samples are from the R. Hay collection, and were previously described by Barker and Milliken (2008). Polished thin sections were prepared at the ARC Centre of Excellence in the Ore Deposits and School of Earth Sciences (University of Tasmania) without using water to avoid dissolution of any water-soluble minerals, if present. Thin sections and a polished block with individual minerals grains (magnetite, clinopyroxene, garnet and perovskite) were studied using a Leica DM2500 P light microscope (St. Petersburg State University), scanning electron microscopes (JEOL 5900LV – Natural History Museum (NHM), London, Hitachi S-3400N – St. Petersburg State University and TESCAN MIRA 3MLU – Institute of Geology and Mineralogy, Novosibirsk), and a Cameca SX-100 electron microprobe (NHM, London). Energy and wavelength-dispersive electron microprobe analyses of minerals were obtained from the above (detailed information available from the authors on request).

3. Results

The Footprint Tuff is a 12–15 cm thick layer consisting of two tuff units with different structures, lithology and content of footprints (Hay, 1987). The lower unit was subdivided by R. Hay in 14 layers and the upper unit consists of 4 layers, each of which was probably deposited from a single eruption. The primary tuff minerals, recognized by Hay (1978, 1987), Barker and Milliken (2008), McHenry (2011) and in this study, are clinopyroxene, nepheline, garnet, melilite, magnetite, perovskite and phlogopite. An unspecified amphibole group mineral has been identified by Barker and Milliken (2008) on the basis of energy-dispersive spectra, but its presence has not been confirmed during this study. In addition, we also found fluorapatite, ilmenite, Ba-bearing sanidine and titanite in the Footprint Tuff samples. Abundant authigenic minerals are represented by calcite, phillipsite and nontronite (Barker and Milliken, 2008).

Published (McHenry, 2011) and new analyses (Tables 1 and 2, Figs. 2–5) of the primary minerals from the Footprint Tuff show that:

(1) clinopyroxene is mostly diopside, sometimes enriched in hedenbergite and aegirine end-members ($Di_{81.1}Hed_{10.5}Aeg_{3.4}others_{4.9}$ to $Di_{42.2}Hed_{41.6}Aeg_{14.8}others_{1.5}$ in mol.%), and rarely aegirine-augite ($Di_{41.6}Hed_{34.9}Aeg_{20.8}others_{2.7}$ to $Di_{25.8}Hed_{45.0}Aeg_{16.3}others_{13.0}$ in mol.%) (Fig. 2);
(2) garnet has a variable composition (7.6–17.8 wt.% TiO_2) and belongs to an andradite-schorlomite solid solution with Fe^{3+} = 0.48–1.29 apfu (atoms per formula unit) and Ti = 0.48–1.13 apfu (Fig. 3);
(3) melilite is of a Na–Al rich variety (4.1–4.8 wt.% Na_2O and 7.7–8.8 wt.% Al_2O_3) and on the basis of the Mg, Al and Fe^{2+} cation proportions in the T1 site it can be further classified as åkermanite and alumoåkermanite (Fig. 4);
(4) magnetite contains a significant amount of Ti (between 7.0 and 14.8 wt.% TiO_2, and up to 17.7 wt.% TiO_2 according to McHenry (2011)), it is also enriched in Mg (up to 7.2 wt.% MgO) and Al (up to 3.3 wt.% Al_2O_3) (Fig. 5). Statistical analysis

Table 1
Selected analyses of clinopyroxene, garnet and melilite from the Laetolil Tuff 7 (Footprint Tuff).

Mineral	Clinopyroxene						Garnet						Melilite	
Analysis	56	54	50	46	18	13	77	74	72	67	65	66	9	5
SiO_2	50.97	50.36	50.99	48.63	52.53	51.64	32.39	30.60	29.97	27.83	26.53	26.61	42.83	43.43
TiO_2	1.74	1.93	1.35	2.09	0.46	0.53	7.55	11.16	12.19	15.78	17.46	17.79		0.04
Al_2O_3	2.80	3.07	3.01	4.88	0.37	0.71	0.90	2.17	2.08	2.37	1.99	1.66	7.91	8.20
Fe_2O_3	3.28	3.87	3.28	4.37	4.03	7.62	23.23	19.57	19.07	17.00	16.46	16.54	1.52	1.41
FeO	2.25	2.03	3.10	2.15	9.20	10.44	2.48	3.03	3.13	3.80	3.50	3.93	3.03	3.11
MnO	0.08	0.10	0.11	0.09	0.46	0.58	0.33	0.24	0.23	0.22	0.22	0.22	0.08	0.10
MgO	14.89	14.65	14.33	13.68	10.35	7.50	0.52	0.91	0.95	1.12	1.33	1.27	6.41	6.34
CaO	24.52	24.46	24.25	24.30	22.05	19.18	32.52	32.44	32.48	32.04	31.77	31.94	33.16	33.09
Na_2O	0.48	0.51	0.51	0.49	1.48	2.82	0.12	0.09	0.09	0.12	0.16	0.16	4.31	4.57
K_2O													0.08	0.08
SrO													0.25	0.20
V_2O_3							0.23	0.13	0.15	0.08	0.06	0.14		
Total	101.01	100.99	100.93	100.68	100.92	101.01	100.27	100.34	100.34	100.35	99.48	100.27	99.57	100.57
Si	1.864	1.845	1.871	1.793	1.976	1.968	2.728	2.566	2.517	2.345	2.261	2.255	1.954	1.959
Ti	0.048	0.053	0.037	0.058	0.013	0.015	0.478	0.704	0.770	1.000	1.119	1.134		0.001
Al	0.121	0.133	0.130	0.212	0.016	0.032	0.089	0.214	0.206	0.235	0.200	0.166	0.425	0.436
Fe^{3+}	0.090	0.107	0.091	0.121	0.114	0.218	1.472	1.235	1.205	1.078	1.055	1.055	0.052	0.048
Fe^{2+}	0.069	0.062	0.095	0.066	0.289	0.332	0.175	0.212	0.220	0.267	0.249	0.279	0.116	0.117
Mn	0.002	0.003	0.003	0.003	0.015	0.019	0.024	0.017	0.016	0.016	0.016	0.016	0.003	0.004
Mg	0.812	0.800	0.784	0.752	0.580	0.426	0.065	0.114	0.119	0.141	0.169	0.160	0.436	0.426
Ca	0.961	0.960	0.953	0.960	0.889	0.782	2.934	2.914	2.922	2.893	2.901	2.900	1.621	1.599
Na	0.034	0.036	0.036	0.035	0.108	0.208	0.020	0.015	0.015	0.020	0.026	0.026	0.381	0.400
K													0.005	0.005
Sr													0.007	0.005
V							0.016	0.009	0.010	0.005	0.004	0.010		
Total	4.000	4.000	4.000	4.000	4.000	4.000	8.000	8.000	8.000	8.000	8.000	8.000	5.000	5.000

The analyses are organized in order of decreasing of atomic proportion of Mg for clinopyroxene, Fe^{3+} for garnet and Al for melilite. Fe_2O_3 and FeO are calculated from charge balance 4 cations and 6 O (clinopyroxene), 8 cations and 12 O (garnet) and 5 cations and 7 O (melilite). Blank fields indicate that their abundances are below detection levels.

Table 2
Statistical parameters for the magnetite from the Laetolil Tuff 7 (Footprint Tuff).

Parameter	X	S	RSD	SK	KR	N
Low Mg–Ti population						
MgO	2.72	0.30	11.0	1.8	3.4	41
Al_2O_3	2.16	0.35	16.0	0.5	1.7	41
SiO_2	0.04	0.01	29.3	1.3	2.1	40
CaO	0.07	0.03	46.2	0.2	−1.3	34
TiO_2	9.69	0.41	4.3	1.7	2.6	41
V_2O_3	0.13	0.02	15.3	0.8	0.1	41
Cr_2O_3	0.03	0.01	9.0	3.6	13.0	13
MnO	0.75	0.08	10.2	−0.6	0.2	41
ZnO	0.06	0.01	13.6	−0.1	−1.5	17
FeO	80.52	0.85	1.1	−2.0	4.6	41
Total	96.17					
Calculated		Formulae (O = 4, cations = 3)				
Fe_2O_3	49.47					
FeO	36.01	$(Fe^{2+}_{0.83}Mg_{0.15}Mn_{0.02})_{\sum 1.00}(Fe^{3+}_{1.37}Ti_{0.27}Fe^{2+}_{0.27}Al_{0.09})_{\sum 2.00}O_4$				
Total	101.12					
High Mg–Ti population						
MgO	4.95	1.24	25.0	0.2	−1.4	14
Al_2O_3	2.86	0.28	9.7	0.3	−1.5	14
SiO_2	0.13	0.15	118.6			8
CaO	0.10	0.06	58.6	0.9	1.5	10
TiO_2	12.65	2.75	21.7	0.7	−0.4	14
V_2O_3	0.14	0.01	10.5			4
MnO	0.71	0.16	22.3	0.6	−0.7	14
FeO	73.58	3.68	5.0	0.1	−1.6	14
Total	95.13					
Calculated		Formulae (O = 4, cations = 3)				
Fe_2O_3	42.75					
FeO	35.12	$(Fe^{2+}_{0.71}Mg_{0.27}Mn_{0.02})_{\sum 1.00}(Fe^{3+}_{1.18}Ti_{0.35}Fe^{2+}_{0.35}Al_{0.12})_{\sum 2.00}O_4$				
Total	99.41					

X – average wt.%; S – standard deviation wt.%; RSD – relative standard deviation %; SK – skewness (asymmetry); KR – kurtosis (excess); N – number of analyses.

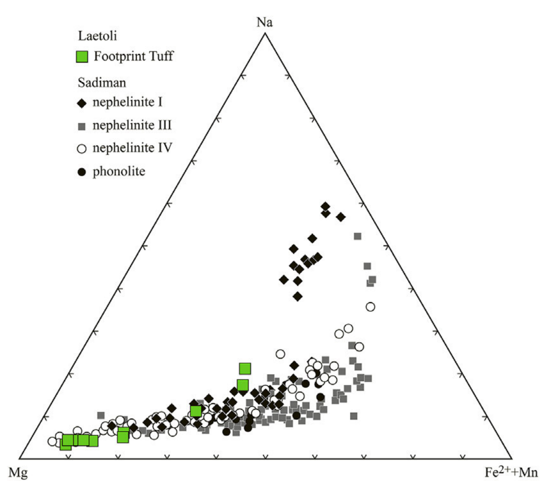

Fig. 2. Compositional variations of the clinopyroxene in the system Na–Mg–Fe^{2+} + Mn (at.%). Sadiman data are from Zaitsev et al. (2012).

of the original 48 microprobe analyses and 26 analyses from McHenry (2011) shows a heterogeneous magnetite composition within the Footprint Tuff, and two mineral populations can be recognized on the basis of MgO, Al_2O_3 and TiO_2 concentrations (Table 2). A low Mg–Ti magnetite variety occurs in the lower part of the tuff, while a high Mg–Ti magnetite is observed in the upper part of the tuff.

Ilmenite, previously unknown from the Footprint Tuff, occurs as subhedral crystals up to 40 μm in size, and contains a significant amount of Mn (4.2–10.9 wt.% MnO) and low Mg (0.1–0.2 wt.% MgO).

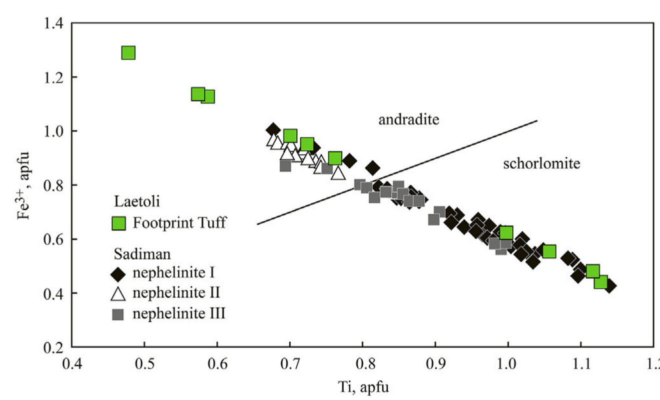

Fig. 3. Compositional variations of the garnet on its Y site (Ti vs Fe^{3+}, atoms per formula unit); line with slope 1:1 separates fields of andradite and schorlomite. Sadiman data are from Zaitsev et al. (2012).

Detailed petrographic and SEM investigations of the magnetite (low Mg–Ti variety) revealed the presence of melt inclusions in large (>100 μm) crystals (Fig. 6). The inclusions are 5–50 μm in size and commonly consist of silicate glass (ca. 93–98 vol.%) and carbonate bleb(s) (ca. 2–7 vol.%). This phase composition seems to show a silicate–carbonate liquid immiscibility phenomenon within inclusions before, or after, their entrapment by magnetite. The silicate glass is silica-undersaturated and peralkaline with a (Na + K)/Al ratio between 1.4 and 2.5 (Table 3). The carbonate-rich globule is characterized by low analytical totals, low silica and high calcium and alkali content (8.3–9.2 wt.% $Na_2O + K_2O$), with a clear carbon peak in its energy dispersive X-ray spectrum. The compositional difference between silicate glass and carbonate-rich globules is clearly shown on the X-ray element distribution maps

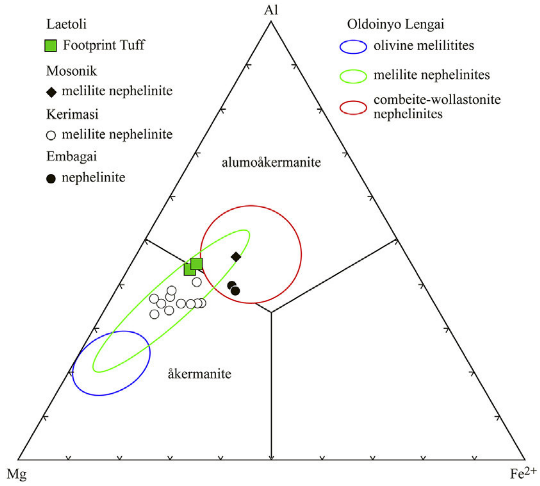

Fig. 4. Composition variations of the melilite in the system Al–Mg–Fe^{2+} (T1 site, at.%). Oldoinyo Lengai data are from Wiedenmann et al. (2009, 2010), Embagai data are from Mollel (2007).

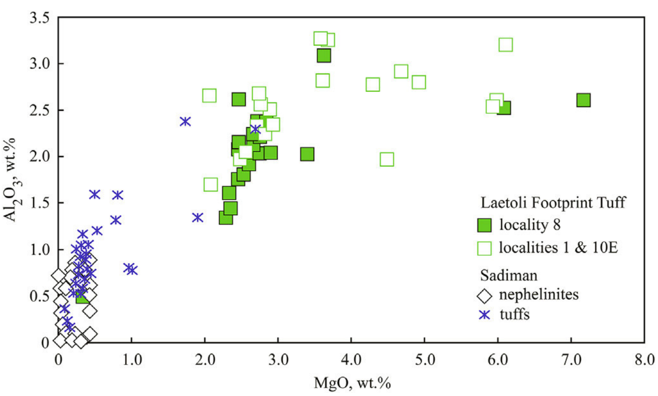

Fig. 5. Relationships between MgO and Al_2O_3 (wt.%) in magnetite. Laetoli localities 1 and 10E are from McHenry (2011), Sadiman nephelinites data are from Zaitsev et al. (2012).

(Fig. 1S). Both silicate and carbonate components contain a significant amount of volatile elements: phosphorus, sulphur, fluorine and chlorine (Table 3). In addition melt inclusions with silicate–carbonate immiscibility were also found in diopside, Ti-bearing andradite and perovskite.

4. Discussion

Available data show that the Sadiman volcano and the Laetolil Footprint Tuff 7 are generally similar in terms of mineralogy. Both localities contain minerals with similar compositions: diopside, hedenbergite, aegirine-augite, nepheline, andradite, schorlomite, perovskite and titanite (Hay, 1978; McHenry, 2011; Zaitsev et al., 2011, 2012). This mineral assemblage is typical for silica-undersaturated alkaline to peralkaline rocks such as nephelinites and to a lesser degree phonolites (Dawson, 2008).

The melilite-group minerals, åkermanite and alumoåkermanite, which are known at Laetoli, were not found at Sadiman, either as unaltered minerals themselves or their pseudomorphs. It is well established from Oldoinyo Lengai volcano (Wiedenmann et al., 2009, 2010) that the composition of the melilite-group minerals, particularly their content of Na and Al, reflect the degree of melt fractionation from which these mineral were crystallized. The composition of the Laetolil Footprint Tuff 7 åkermanite-alumoåkermanite, $(Ca_{1.49-1.64}Na_{0.36-0.43})(Mg_{0.40-0.44}Al_{0.39-0.46}Fe^{2+}_{0.14-0.16}Fe^{3+}_{0-0.07})(Al_{0.01-0.04}Si_{1.96-2.04})O_7$ (Table 1, Fig. 4), indicates mineral formation from an evolved (fractionated) melt, similar to that from which melilite nephelinites (and even highly evolved combeite nephelinites) crystallized at Oldoinyo Lengai.

Furthermore, the magnetite composition from the Laetolil Footprint Tuff 7 and that from the Sadiman volcano (nephelinites and tuffs) show a significant difference between the minerals from both localities. This is particularly evident from the content of MgO and Al_2O_3 (Fig. 5), and this argues against the deposition of magnetite in Laetoli during the eruption of Sadiman. The Footprint Tuff 7 is quite heterogeneous (Fig. 2.6 in Hay, 1987) and the diverse magnetite, as well as garnet compositions suggest several ash deposition events, possibly even from different sources.

The occurrence of silicate–carbonate immiscible melt inclusions in magnetite from the Footprint Tuff could be considered an indication of carbonatitic activity in the volcanic source of the Laetoli material. Melt inclusions with silicate–carbonatite immiscibility are known from the Oldoinyo Lengai nephelinites (Mitchell, 2009; Mitchell and Dawson, 2012; Sharygin et al., 2012), Kerimasi plutonic silicate rocks and carbonatites (Guzmics et al., 2011, 2012), whereas melt inclusions in nephelinites from the Sadiman and Mosonik volcanoes commonly show silicate-CaF_2 immiscibility (Zaitsev et al., 2011, 2012). The carbonate-rich globules from immiscible magnetite-hosted inclusions in the Laetolil tuff are characterized by a more calciocarbonatite rather than natrocarbonatite composition. Unlike at Oldoinyo Lengai and Kerimasi, in the Laetolil tuff the separation into silicate and carbonate liquids was not complete. This is evident from the high contents of SiO_2, TiO_2, Al_2O_3 and FeO in its carbonate-rich part (Table 3). Typically, liquid immiscibility in a carbonate–silicate melt leads to low contents of these components in the carbonate-rich fraction (Mitchell, 2009; Sharygin et al., 2012).

Manganoan ilmenite from the Laetoli Footprint tuff, occurring as single crystals or overgrown by titanite, may also be an indication of a carbonatitic source, although ilmenite in many carbonatite localities contains magnesium and/or niobium (Chakhmouradian and Zaitsev, 1999). High-Mn and low-Mg ilmenite are also known from a diverse variety of rocks, including kimberlites (Chakhmouradian and Mitchell, 1999) and foid-bearing monzogabbro (Marks et al., 2008), and hence it is not a good indicator of source rock.

The critical point in the relationship between the Sadiman volcano (and/or other potential sources) and the Laetolil tuff is the age of volcanism in the Crater Highlands and nearby Gregory Rift which produced nephelinitic ashes (Table 4). Recent geochronological studies have shown that, in some cases, there is a large discrepancy in published age data for a single locality. For example, Essimingor volcano was dated as 4.89–3.20 Ma by Evans et al. (1971), 8.1–7.35 Ma by Bagdasaryan et al. (1973) and 5.91–5.76 Ma by Mana et al. (2012). Possible explanations for the observed age differences at a particular locality include uncertainty in the precise location of the investigated samples, ^{40}Ar excess or loss, particularly in nepheline or xenocrystic mineral grains being erroneously dated as belonging to the volcanic activity. For a detailed discussion on problems with published geochronological data see Fitch et al. (1978), Mollel et al. (2011, 2012) and Mana et al. (2012).

Sadiman is the oldest volcano among the Crater Highlands volcanoes and published K–Ar ages indicate a wide range of the volcano activity: 4.5 Ma (Bagdasaryan et al., 1973), 3.7 Ma (Curtis and Hay, 1972) and 3.3 Ma (Manega, 1993). Recently samples from Laetoli and Sadiman were analyzed and high-precision ages from $^{40}Ar/^{39}Ar$ dating were obtained for Laetoli (Deino, 2011) and Sadiman (Mollel et al., 2011). Nephelinites from Sadiman were

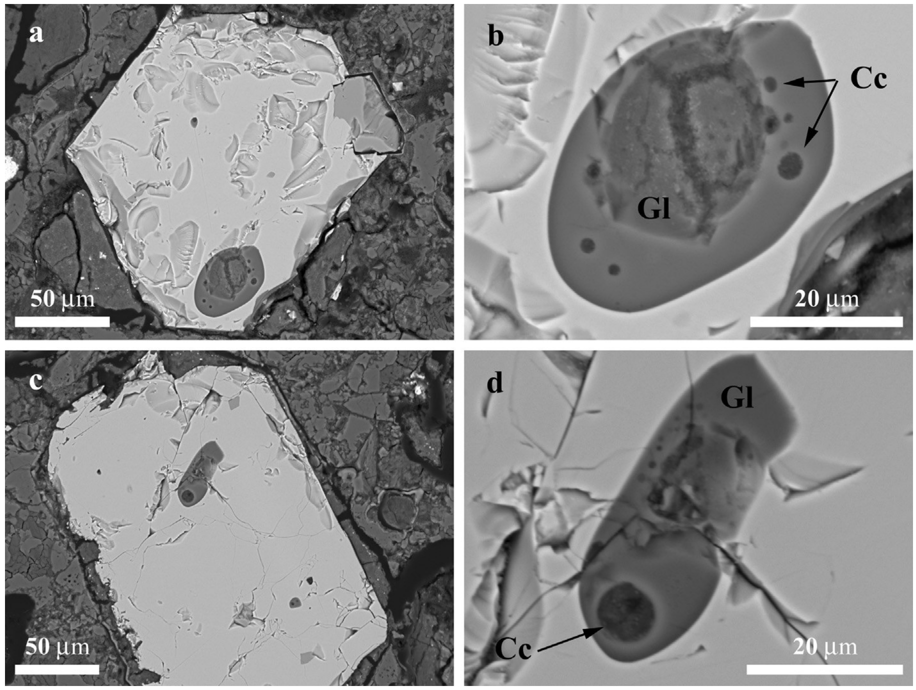

Fig. 6. Silicate–carbonate melt inclusions in magnetite. (a, c) general view, (b, d) details of (a) and (c); Gl – silicate glass, Cc – carbonate globules. Back-scattered electron images.

Table 3
Composition (wt.%) of the melt inclusions in magnetite.

Inclusion	1	1	2	1	2
Phase	Glass			Carbonate globule	
SiO_2	41.41	42.18	38.56	13.65	10.59
TiO_2	1.79	1.79	2.37	1.06	1.04
Al_2O_3	11.90	11.84	9.72	3.04	2.23
FeO	7.00	7.69	12.60	4.39	4.03
MnO	0.34	0.33			0.30
MgO	3.43	3.73	2.28	1.63	2.49
CaO	15.61	15.47	15.20	25.36	27.09
Na_2O	11.67	7.58	12.68	5.50	6.29
K_2O	4.28	3.71	3.33	3.72	2.01
P_2O_5	1.25	1.13	1.21	3.25	6.62
SO_3	0.60	0.66	0.35	2.30	2.01
F	2.74	2.79	0.45	1.18	2.95
Cl	0.40	0.45	0.36	0.30	0.41
–O=F,Cl	1.24	1.28	0.27	0.56	1.33
Total	101.18	98.07	98.84	64.82	66.73

Inclusion 1 – Fig. 6b; inclusion 2 – Fig. 6d; Blank fields indicate that their abundances are below detection levels.

dated to 4.63 (possibly 4.8)–4.02 Ma; tuffs from the Lower Laetolil unit to 4.36–3.85 Ma and tuffs from the Upper Laetolil unit to 3.85–3.63 Ma (the interpolated age for the Footprint Tuff 7 is 3.66 Ma). Clearly, Sadiman samples with ages of 3.7 and 3.2 Ma should be re-investigated to verify these young ages for the volcano.

If the 3.7–3.3 Ma Sadiman ages are correct, then the poorly studied nephelinitic to phonolitic Mosonik volcano (Dawson, 2008), located about 100 km to north-east from Laetoli, with an age between 3.5 Ma (Manega, 1993) and 3.2 Ma (Isaac and Curtis, 1974), could be a potential source for some of the Laetolil tuffs (Table 4). Mosonik is a strongly eroded volcano with heavy vegetation and just a few outcrops. Field observations show that the volcano is predominately made up of nephelinitic to phonolite nephelinitic lavas with phonolites and ijolite-melteigites occurring as xenoliths in lavas. Carbonatites, either volcanic or plutonic, have not been observed in any outcrop, but plutonic carbonatites occur as pebbles or boulders (up to 50 cm in diameter) in streams inside the volcano. Two carbonatite samples contain xenoliths of nephelinite and phonolite. Our new data also shows that the volcano also contains melilite nephelinites (Fig. 7a) with the alumoåkermanite composition of $(Ca_{1.51}Na_{0.49})(Al_{0.44}Mg_{0.32}Fe^{2+}{}_{0.19}Fe^{3+}{}_{0.05})(Si_{2.00}O_7)$ (Fig. 4).

Nephelinites from the Embagai (about 75 km to north-east from Laetoli) and Kerimasi volcanoes (about 90 km in the same direction), also containing alumoåkermanite and åkermanite (Fig. 7b) similar in composition to the Laetoli mineral (Fig. 4), are much younger compared to the Laetolil Footprint Tuff 7 (Table 4): Embagai is 1.2–0.6 Ma old (Manega, 1993; Mollel, 2007), and Kerimasi is 1.1–0.4 Ma old (Macintyre et al., 1974).

Essimingor volcano, with all published age data from 8.1 to 3.2 Ma (Table 4), and the presence of minor to accessory melilite in some of its nephelinites (Mana et al., 2012), could be a source for

Table 4
Summary of geochronological and geological information for the possible source volcanoes.

Locality	Laetolil Footprint Tuff	Essimigor	Sadiman	Mosonik	Embagai	Kerimasi
Age (before 2000), Ma K–Ar and $^{40}Ar/^{39}Ar$		4.89(0.09)–3.20(0.06)[2] 8.1(1)–7.35(0.65)[3]	4.5(0.4)[3] 3.32(0.06)[5] 3.73[6]	3.18(0.08)[8] 3.53(0.06)[5]	1.20(0.01)–0.55(0.02)[5]	1.1–0.4[9]
Age (after 2000), Ma $^{40}Ar/^{39}Ar$	3.66[1]	5.91(0.01)–5.76(0.02)[4]	4.63(0.05)–4.02(0.02)[7]		1.20(0.06)–0.80(0.40)[7]	
Rock types	Melilite nephelinite	Picrite, tephrite, melilite nephelinite, nephelinite, phonolite	Nephelinite, phonolitic nephelinite, phonolite	Melilite nephelinite, nephelinite, phonolitic nephelinite, phonolite	Limburgite, trachybasalt, melilite nephelinite, nephelinite, phonolite	Melilite nephelinite, nephelinite, phonolitic nephelinite
Carbonatites	Possibly calcite carbonatite	Not known	Not known	Calcite carbonatite	Not known	Calcite carbonatite
Possible source for Laetolil Footprint Tuff		Too old	Yes	Yes	Too young	Too young
Future work		Confirmation of 4.89–3.2 Ma age, melilite study	Confirmation of 3.73–3.32 Ma age, search for melilite-bearing rocks	Detailed geochronological study		

Geochronological data are from 1 – Deino (2011), 2 – Evans et al. (1971), 3 – Bagdasaryan et al. (1973), 4 – Mana et al. (2012), 5 – Manega (1993), 6 – Curtis and Hay (1972), 7 – Mollel (2007), 8 – Isaac and Curtis (1974) and 9 – Macintyre et al. (1974). Geological data are from Mollel (2007), Dawson (2008), Mana et al. (2012) and Zaitsev et al. (2012).

the Laetoli beds. However, if it was active between 5.91 and 5.76 Ma only and other age data are erroneous (Mana et al., 2012), then Essimongor is too old to be the source even for the Lower Laetolil Tuffs (4.36–3.85 Ma).

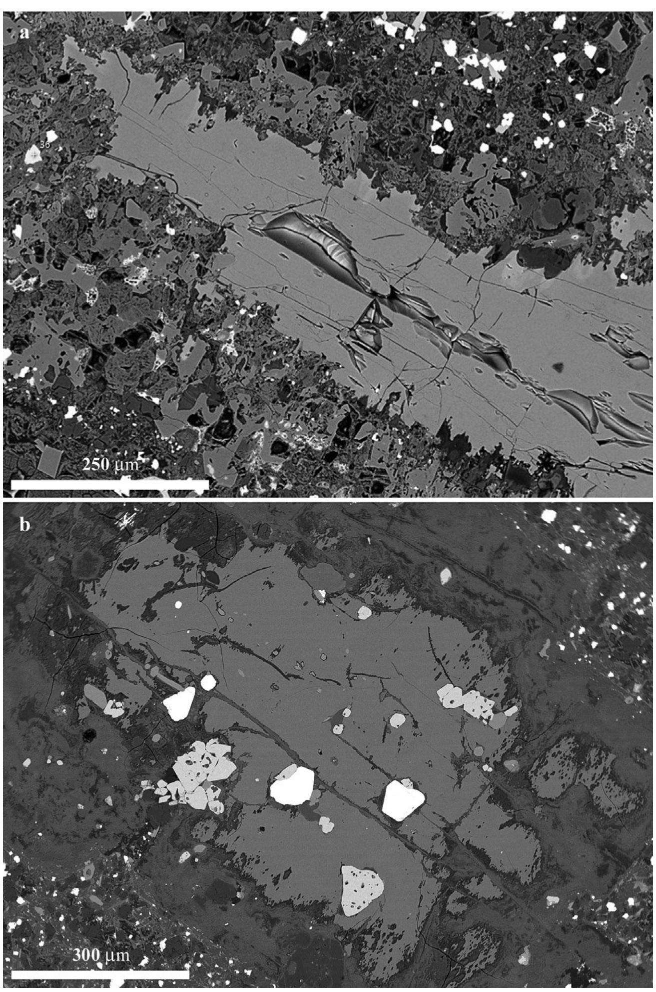

Fig. 7. Corroded melilite phenocrysts in nephelinites: (a) Mosonik volcano, sample MOS 7b; (b) Kerimasi volcano, sample K 94–24, white inclusions – magnetite, light gray inclusions – perovskite (petrology collection at the Natural History Museum, London, BM.1995,P6(46)). Back-scattered electron images.

Obviously, the large inconsistency in available age determinations for the Crater Highlands and Gregory Rift volcanoes shows the importance of future detailed geochronological studies and particularly the re-investigation of samples from pre-2000 publications.

5. Conclusions

With the currently available mineralogical, geochemical and geochronological data for Sadiman and Laetoli volcanic rocks we conclude that the Sadiman volcano was not the source of the Laetoli Footprint Tuff, where 3.66 Ma old footprints of *A. afarensis* were well preserved. This is in particular due to the lack of melilite within Sadiman lavas and tuffs. In contrast this mineral is present, as fresh material or complete pheudomorphs, in several Upper Laetolil beds. Significant difference in magnetite composition from Laetoli and Sadiman, particularly in Mg, Al and Ti content, also point to a source which is different from Sadiman. At the same time, our new data from melt inclusions hosted by magnetite supports Hay's conclusion that Laetolil ash could have erupted from a carbonatitic volcanic source. This possibility had been previously ruled out by Barker and Milliken (2008).

An exact source (or sources) for the Laetolil beds is still unknown. Mosonic volcano could be a potential source owing to the occurrence of melilite nephelinite, but the uncertainty in its age and its distance from Laetoli raise doubts. It is also possible that an unknown source was later covered by lavas and tuffs from the Lemagarut volcano, which is 2.4–2.2 Ma old (Mollel et al., 2011). If this was the case, we may never find the real source of the famous Footprint Tuff.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jafrearsci.2015.07.023.

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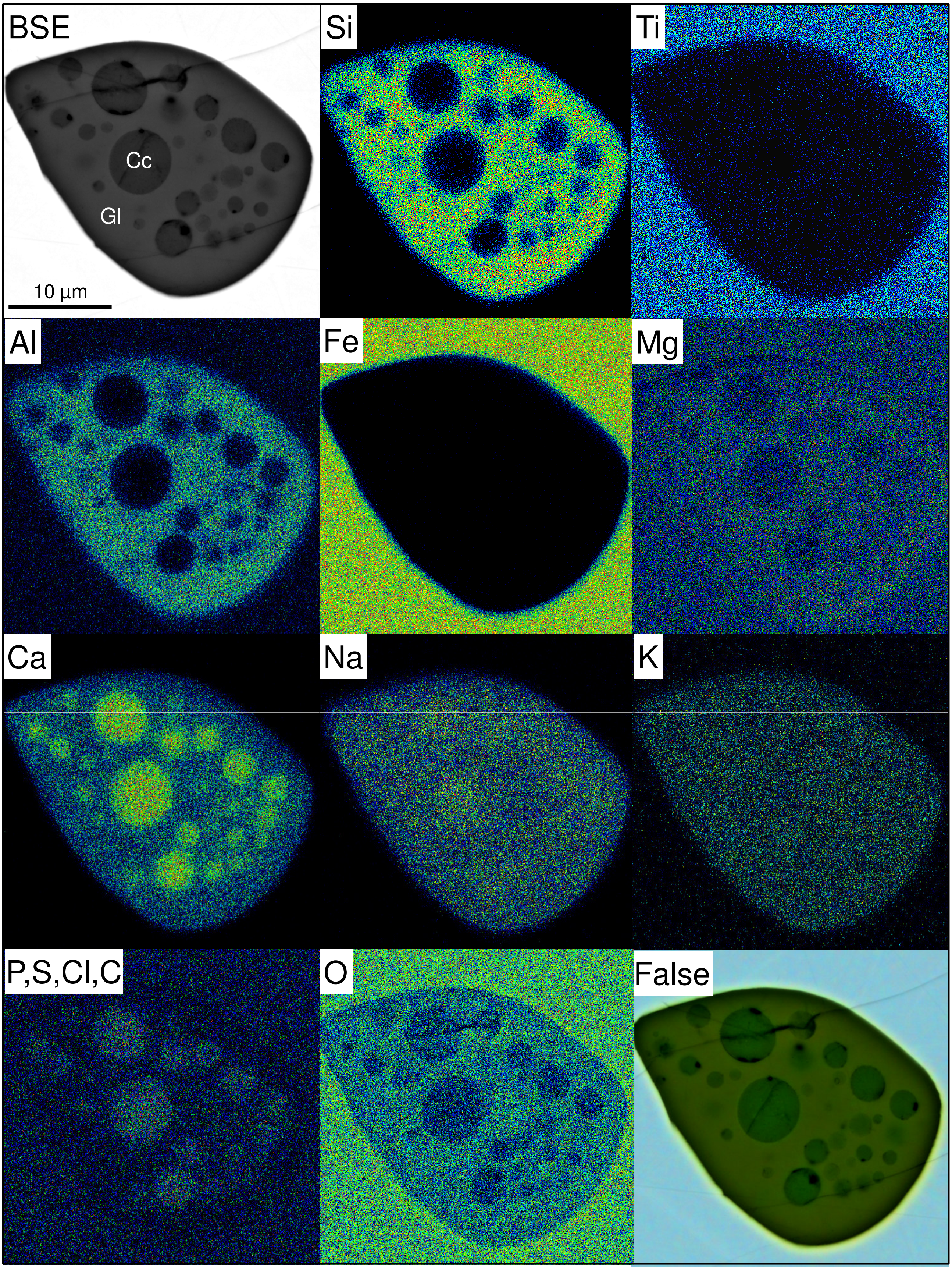

Fig. 1S. BSE image and X-ray element distribution maps for an melt inclusion in magnetite. Gl – silicate glass, Cc – carbonate globules.