Salt-bearing fumarole deposits in the summit crater of Oldoinyo Lengai, Northern Tanzania: interactions between natrocarbonatite lava and meteoric water

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Abstract

Oldoinyo Lengai in the Northern Tanzania rift is the only active nepheline–carbonatite stratovolcano. We report the discovery of thermonatrite, aphthitalite, halite and sylvite fumarole deposits on recent natrocarbonatite lava flows erupted in the summit crater during the wet season. These salt deposits occur as delicate, concave fringes or tubes that line the cooling cracks in the lava flows and consist of intergrowths of euhedral crystals. The presence of a dark altered zone, depleted in halides and alkalies, adjacent to cooling cracks and observations of steam fumaroles emanating from the fractures suggest that the salts are formed by sublimation from saturated vapours generated by the extrusion of lavas over meteoric water. The crystallisation sequence recorded in the salts suggests that mixing between meteoric steam and magmatic $\text{CO}_2$ and $\text{H}_2\text{S}$ occurs at high temperatures resulting in the sublimation of carbonates and sulphates. At lower temperatures the vapours are dominated by meteoric steam and sublime halides. The high solubility of the fumarole salts within meteoric water and their formation only during the wet season implies that these are ephemeral deposits that are unlikely to be preserved in the geological record.

Keywords: fumarole deposits; Oldoinyo Lengai crater; natrocarbonatite lava

1. Introduction

Oldoinyo Lengai, northern Tanzania, is the only volcano in the world that is currently erupting carbonatite lava and is the only active volcano in the East African Gregory Rift. Carbonatites are igneous rocks containing $>50\%$ carbonate minerals (Le Maitre, 1989) and are relatively rare, occurring at approximately 330 localities worldwide (Woolley, 1989). Most carbonatites are found in intrusive complexes as plutonic rocks often in association with alkaline silicate rocks. However, carbonatite lavas and pyroclastics are known from a number of localities that vary in age from Precambrian (Qassiarsuk, Greenland) to Recent (e.g. Kerimasi, northern Tanzania). Oldoinyo Lengai is unique amongst carbonatites in that it erupts alkaline carbonatite (natrocarbonatite) lavas rather than calcium or magnesium-dominated carbonatites typical of other extrusive occurrences (Woolley, 1989).

The natrocarbonatite lavas of Oldoinyo Lengai have unusual rheological properties with viscosities smaller than those of any other terrestrial lava and
are extremely hygroscopic (Dawson, 1989). The appearance of the lavas changes from fresh black or dark brown vitreous to dull white flows as they hydrate and has been used to estimate the age of natrocarbonatite flows from photographs (Nyamweru, 1997). These remote observations, mainly from aircraft, have been important in recording the activity within the summit crater. We report the discovery of salt fumarole deposits from the surface of lava flows erupted during the wet season that testify to the rapid alteration of natrocarbonatite lavas through interaction with meteoric water. The mineralogy and textures of the fumarole deposits are investigated in the current work in order to: (1) identify the nature of interactions between natrocarbonatite magmas and meteoric water; (2) constrain the mechanisms by which salt sublimes are deposited from saturated vapors; and (3) evaluate the implications for the solute load in runoff waters from Oldoinyo Lengai.

2. Eruptive activity

The recent activity at Oldoinyo Lengai has been restricted to the extrusion of natrocarbonatite lavas in the active northern summit crater with periodic vesuvian and sub-plinian eruptions of ash (Dawson et al., 1995a and references therein). The lavas were first recognised as natrocarbonatites in the 1960s; however, violent eruptions in 1966 and 1967 excavated the crater to a depth of 150 m and were followed by a long period of inactivity that precluded further study. Explosive eruptions in 1983 have been followed by the intermittent eruption of natrocarbonatite lavas in the summit crater (Nyamweru, 1997; Dawson et al., 1995a).

The eruptive style has been characterised by the construction of multiple generations of hornitos from which natrocarbonatite flows extrude to slowly fill the crater. Small scale lava fountaining and the formation of lapilli layers in the crater has occurred periodically and occasional ash eruptions have been reported (e.g. Dawson et al, 1995b). In 1993 thicker, viscous lava flows were erupted that consisted of mixed carbonate-silicate magma; however, despite the expectation that this marked a change in eruptive style (Church and Jones, 1995), the eruption of low viscosity natrocarbonatites has resumed and continues at the present time.
3. Observed activity

Observations on the third and fourth April, 1999 during the wet season reveal that the lavas infilling the active northern crater have reached the level of the lapilli and ash crater rim on the north, east and south-west sides of the crater. Natrocarbonatite lava flows, emanating from the crater, have flowed several thousand feet down the flanks of the volcano in the north and east. Two fresh natrocarbonatite flows, each ~30 m³ in volume (Fig. 1), were found in the crater that extruded from hornitos named Mary and Peter and had probably erupted at 3.00 am on the third April when a steam plume several thousand feet in height was observed above the summit. The surface temperatures of the flows, which were up to 100°C, indicate that the lavas were still cooling after eruption and thus suggest eruption at approximately the same time as the steam plume. Both lava flows are pahoehoe and have numerous, well developed leveed channels with pahoehoe tongues where the lavas have breached the levees (Fig. 2). Close to the hornitos, the flows have down-cut through the existing flows and reside in deep channels. Small amounts of natrocarbonatite lapilli found around the hornitos also suggest restricted lava fountaining. Although no further extrusive activity occurred during the rest of the third or fourth of April, rumbling and the sound of splashing lava could be heard from hornito Mary.

In contrast with previous observations, significant fumarole activity occurred from all hornitos in the crater throughout the third and fourth April (Fig. 3). Numerous fumaroles also emanated from fissures in the crater rim and are associated with extensive deposits of native sulphur. Most fumaroles were associated with relatively low-temperature steam, although high temperature colourless gas, producing significant heat shimmer, came from active hornito Peter and blue and black smoke was emitted from hornito Diablo. A strong odour of H₂S was noted at all times. Previous
Measurements of the fumarole gases from the crater of Oldoinyo Lengai during the dry season (Koepenik et al., 1996) indicate that volcanic gases are dominated by CO₂ with lesser amounts of H₂O and minor H₂S, HCl and HF. The observation that new steam fumaroles appeared shortly after precipitation at the summit suggests that the high fumarole activity was related to the vaporisation of meteoric water. Smaller steam-dominated fumaroles also emanated from cooling cracks in the fresh natrocarbonatite flows and are associated with white crystalline salt deposits described in more detail below.

4. The occurrence of fumarole salt deposits

Delicate fringes and tubes of white crystalline salts were found lining cooling cracks in the recent natrocarbonatite lava flows (Fig. 4). The salt fringes, which extend 1–3 cm above the flow top, are concave upwards and have vertical ribs due to variations in thickness of the sheet. In places the curvature of the fringes increases along their length to form tubes with further fringes developed over sub-spherical openings in the upper surface. Adjacent to the cooling cracks the vitreous grey lava becomes dull and dark grey, and has evidently been altered. The dark grey alteration contrasts with the whitened margins of the natrocarbonatite tongues (Fig. 5) that strongly resemble those altered lavas formed in the dry season by extended exposure to the atmosphere. These altered tongues are raised above the surface of the underlying lavas producing a void space and were presumably formed shortly after eruption since little further alteration of the surface occurred over the period of observation.

The surfaces of older flows in the northern crater...
have been altered to a brown colour and are watersaturated in places presumably from heavy rains that fell on the crater on the first and second of April. The steam plume observed during the eruption of the flows, the steam fumaroles emanating from cracks and the altered margins of the flows all probably formed due to the extrusion of natrocarbonatite lava over the water-saturated crater floor.

5. Samples and techniques

Samples of fresh natrocarbonatite, salt deposits and the dark altered natrocarbonatite adjacent to cooling cracks were collected from both the recent flows. The samples were collected prior to the first rainfall after the eruption, in which the salt fringes were largely dissolved and lost, and were placed in sealed plastic containers with silica gel desiccant. On return the lava samples were still in a fresh vitreous state and all samples were transferred to a desiccator. Probe mounts were prepared within two weeks of collection by embedding specimens in resin and polishing under oil.

Mineral chemistries were determined using a Hitachi S2500 analytical SEM fitted with a link AN10000 energy dispersive spectrometer. Analyses were performed at an accelerating voltage of 15 kV and beam current of 40 nA against a vanadium gain calibration and internal absorption coefficients. ZAF matrix corrections were applied. Appreciable volatilisation of Na under the beam was minimised by rastering the beam over an area of 25–5 μm². Analytical errors are estimated at 0.5 wt% but are larger (up to 2 wt%) for Na-rich carbonates. All carbonate analyses suffer from low totals due to the volatilisation of Na and carbonate. High magnification backscattered electron images (BEI)
were obtained using a Phillips XL30 field emission SEM.

A Cameca SX50 microprobe operated at 15 kV and 20 nA was used to determine minor element contents by wave dispersive spectroscopy (WDS). Analyses were performed against mineral standards and matrix corrections were applied. Semi-quantitative analyses of carbon and oxygen were obtained by WDS to verify the identification of carbonates and estimate the abundance of the carbonate ion. These were calibrated against a calcite standard (for carbon Kα) and an olivine standard (for oxygen Kα).

Mineral identification was verified by X-ray powder diffraction using a position sensitive diffractometer calibrated to a silicon pattern utilising copper Kα radiation following the methods of Batchelder and Cressey (1998). This instrument allows rapid, high precision phase quantification.

6. Mineralogy and texture of fumarole deposits

Salt fringes and tubes consist of assemblages of thermonatrite Na₂CO₃·H₂O, aphaltitalite (Na,K)₂SO₄, halite NaCl and sylvite KCl. Thermonatrite comprises ~70% by volume of the salt fringes and occurs as intergrown equant euhedral crystals, which adjacent to void spaces within the structure show monoclinic prismatic habits (Fig. 6a). In places laths of thermonatrite also occur. Within the detection limits of the analytical techniques employed, thermonatrites contain no K or other trace elements. Cruciform shaped inclusions containing thermonatrite and cubic halite and sylvite often occur within the larger thermonatrite crystals and have textures that suggest recrystallisation of the thermonatrite and replacement by halite and sylvite (Fig. 6b). Recrystallisation of thermonatrite to polycrystalline, porous masses

Fig. 5. Alteration of the margins of a fresh natrocarbonatite lava flow. The white natrocarbonatite tongues are raised above the level of the underlying lavas and are 5–10 cm thick.
Fig. 6. Backscattered electron images of polished sections through a salt fringe. (a) The fringes consist of layers constructed of thermonatrite (T) crystals separated by void spaces (V) in which aphthitalite laths (A), halite masses (H) and mixed sylvite-halite masses have precipitated. (b) Halite and sylvite also occur as cruciform-shaped inclusions within the thermonatrites. (c) Aphthitalite laths frequently occur as intergrown porous masses presumably formed by precipitation within void spaces. (d) Mixed sylvite–halite masses consist of large pseudohexagonal halite crystals within a finer grained matrix of aligned, cubic halite and sylvite crystals (S and H). (e) Halite and sylvite-rich rims are found on the fumarole-facing sides of the salt fringes. Protrusions with cores of thermonatrite are connected to the main fringe structure by the halite- and sylvite-rich rim.
containing acicular crystals of thermonatrite, <2 \mu m in size, is observed in high magnification BEI.

Aphthitalite constitutes \sim 10% by volume of the fringes and is present as porous masses of interpenetrating, acicular crystals <40 \mu m in length that evidently grew within void spaces between the prismatic thermonatrites (Fig. 6c). In some places aphthitalite is intergrown with thermonatrite laths indicating co-precipitation. Analyses of aphthitalite suggest stoichiometries of (Na_{0.23}K_{0.77})_{2}SO_{4} and are thus close to ideal NaK_{3}(SO_{4})_{2}.

Halides occur as polycrystalline masses up to 100 \mu m in diameter and are restricted to the outer margins of the salt fringes and to voids. Halite aggregates are either dominated entirely by cubic halite crystals or are mixtures of halite and sylvite with individual small crystals in the matrix crystallographically orientated (Fig. 6d). The halite-dominated aggregates are in places overgrown by the mixed halite and sylvite masses suggesting they crystallised first. The occurrence of inclusions of aphthitalite and overgrowths of the halide masses over aphthitalite needles also suggests that halide precipitation occurred after the deposition of the sulphates. Mixed halide aggregates growing on a thermonatrite substrate into void spaces frequently have boundaries consisting of stepped crystal faces and have pseudomoniclinoic morphologies (Fig. 6a). Considering the crystallographic orientation of the component crystals this may suggest that epitaxial nucleation and crystal growth has occurred. Large pseudohexagonal crystals of sylvite up to 50 \mu m in size also occur embedded in the mixed halide matrix (Fig. 6d).

Halite and mixed halide masses commonly also occur as rims along the outer margin of the salt fringes that face the cooling crack. Thermonatrite and aphthitalite are present in these areas; however, the occurrence of protrusions containing cores of thermonatrite linked to the main part of the fringe by the halide-rich rim suggests the halides are either replacing thermonatrite or infilling voids left after the dissolution of this carbonate (Fig. 6e).

7. Petrography of natrocarbonatite lavas

The mineralogies and textures of the unaltered natrocarbonatite lava flows erupted in April 1999 are very similar to those previously described (Church and Jones, 1995; Dawson et al., 1995b). The lavas are dominated by lath-like nyerereite (Na_{0.8}K_{0.2}Ca_{0.5}CO_{3}) and rounded gregoryite (Na_{1.6}K_{0.4}Ca_{0.15}CO_{3}) microphenocrysts set in an aphyric fine-grained matrix dominated by fluorite, Na-carbonate, and sylvite (Fig. 7). Two intergrowth textures are observed in the matrix: (i) a fine-grained, symplectic like intergrowth of fluorite and Na-carbonate, and (ii) a granular intergrowth of sylvite and gregoryite. Larger phenocrysts of nyerereite and gregoryite, up to 2 mm in size, also occur in the lavas although they comprise <2% by volume. The rounded gregoryite phenocrysts exhibit many parallel exsolution lamellae of nyerereite. Alignment of nyerereite phenocrysts and microphenocrysts gives the lavas a trachytic texture.

A wide variety of minor phases are observed in the matrix and as inclusions in the gregoryite phenocrysts including FeMn oxides and sulphides, REE oxides, barytes and apatite. The compositions of these minor phases are similar to those previously reported in natrocarbonatites from Oldoinyo Lengai (Church and Jones, 1995; Dawson et al., 1995b).

The altered natrocarbonatite lavas collected from adjacent to cooling cracks have broadly similar textures and mineralogies to the unaltered lavas; however, significant changes are observed in some phases (Fig. 7c–f). Gregoryite phenocrysts and microphenocrysts are strongly altered and have a cross-hatched appearance due to the selective dissolution of gregoryite relative to the crystallographically controlled nyerereite exsolution lamellae. Small amounts of a fine-grained sodium–calcium carbonate phase are found interstitial to the nyerereite lamellae. The porosity of the gregoryite crystals is >30% by volume and many of the microphenocrysts have been entirely removed leaving rounded cavities. Analyses obtained using a rastered beam indicate decreases in the K/Ca and Na/Ca atomic ratios of the relict gregoryites with the K/Ca ratios falling below those of nyerereite (Fig. 8). Euhedral laths of aphthitalite up to 200 \mu m in length occur in the larger gregoryite phenocrysts and contain numerous lamellar inclusions of nyerereite, some of which extend beyond the margins of the aphthitalite laths and are continuous with exsorption lamellae within the relict gregoryite. The textures of these crystals
Fig. 7. Backscattered electron images of polished sections of natrocarbonatite lavas. (a, b) Unaltered natrocarbonatite consist of nyerereite laths (N) and rounded gregoryite phenocrysts (G) in a matrix consisting of nyerereite microphenocrysts, (i) fine-grained symplectic-like intergrowths of fluorite and Na-carbonate, and (ii) granular intergrowths of sylvite (S) and gregoryite. (c) The textures of altered lavas adjacent to cooling cracks are similar to the unaltered lavas. (d) In the matrix the Na-carbonate and gregoryite have been largely removed to form voids. (e) Gregoryite phenocrysts have also been partially dissolved and have a lattice-like structure formed by the nyerereite exsolution lamellae that remain relatively unaltered. Laths of aphpitaitite (A) occur within the relict gregoryites and are crystallographically orientated relative to the nyerereite lamellae. Irregular patches of sylvite and halite (H) are common in the gregoryite phenocrysts and in the matrix. Halite is frequently found as rims around void spaces.
suggest they grew within the gregoryites around the nyerereite exsolution.

Within the matrix of the altered natrocarbonatite the most obvious change is the absence of halite and sylvite. These phases have evidently dissolved after crystallisation since relict fine-grained symplectic intergrowths do occur but have voids in place of sylvite. Irregular masses of halite and sylvite, however, do occur throughout the matrix and within gregoryite phenocrysts often as rims on cavities. These have evidently been deposited at a late stage after the dissolution of the gregoryite. No changes are observed in the textures or compositions of minor phases present in the matrix or as inclusions in gregoryites.

8. Discussion

The occurrence of the salt deposits strongly suggests that the salt fringes were sublimated from steam-dominated fumaroles generated by the extrusion of natrocarbonatite lavas over the water-saturated older lavas that cover the crater floor (Fig. 9). The origin of the salt fumaroles is thus relatively certain; however, the processes by which they are formed are less obvious. The textures and mineralogy of the salt fringes indicate crystallisation in the following sequence: (1) thermonatrite; (2) aphthitalite; (3) halite masses; and (4) halite–sylvite masses. Within the confines of the sublimation from fumarole gases generated during the cooling of a lava flow, the crystallisation sequence may have arisen simply due to decreases in the temperature of gases escaping from cooling cracks. The maximum temperature of the fumarole gases during formation of the salt fringes must be \( \sim 600^\circ\text{C} \), the solidus temperature of the natrocarbonatite lava.

Changes in fluid composition during progressive leaching of the cooling lava may also be important in controlling the crystallisation sequence. Unfortunately no experimental data are available on the system \( \text{Na}_2\text{CO}_3–\text{NaCl–KCl–NaK}_3(\text{SO}_4)_2–\text{H}_2\text{O} \) by which the fluid evolution can be constrained. However, experimental data in the binary systems of \( \text{NaCl} + \text{H}_2\text{O} \) and \( \text{KCl} + \text{H}_2\text{O} \) do suggest that at 1 atm and the highest temperatures of \( \sim 600^\circ\text{C} \) salts and vapour are in equilibrium and salts should crystallise from the fumarole gases (Pitzer and Pabalan, 1986; Chou et al., 1992). The crystallisation of thermonatrite without other phases as the first sublimate thus suggests changes in the vapour composition with temperature.

Magmatic gases such as \( \text{CO}_2 \) and \( \text{H}_2\text{S} \) are likely to be present in higher concentrations at higher rather than at lower temperatures since they are lost rapidly by degassing after eruption. The crystallisation of thermonatrite and aphthitalite as the first sublimes may therefore have occurred from an alkali-bearing \( \text{CO}_2 + \text{H}_2\text{O} + \text{H}_2\text{S} \) gas generated by mixing of

![Fig. 8. The compositions of gregoryite and nyerereite as atomic ratios measured by wide beam (25 \( \mu\text{m}^2 \)) EDS analyses. Relict gregoryites from altered natrocarbonatite adjacent to the cooling cracks are shown as solid circles, gregoryites from unaltered natrocarbonatite are shown as open circles. Nyerereites from altered and unaltered lavas are shown as solid squares. The dashed line shows the effect of the nyerereite exsolution lamellae on the wide beam analyses of the unaltered gregoryites.](image)

![Fig. 9. A schematic diagram illustrating the formation of salt fringes. Alkali and chlorine-bearing ground water is heated by the overlying natrocarbonatite and injected as steam through the lava flow. At high temperature (\( \sim 600^\circ\text{C} \)) the steam is mixed with magmatic gases (principally \( \text{CO}_2 \) and \( \text{H}_2\text{S} \)) and precipitates thermonatrite once released through cracks in the flow top. At the margins of flows steam escaping from below the lava flow produces a void space raising the lava tongues above the underlying lavas and altering the overlying flow. Once the flow has solidified the gases become \( \text{H}_2\text{O} \)-dominated and leach sylvite and gregoryite adjacent to the cooling cracks. Halite and sylvite precipitate from the fumarole gases due to rapid cooling as they are released from the flow top.](image)
maggmatic gases and those generated by the vaporisation of meteoric water contained in the underlying lavas. These fluids would probably already be saturated in alkalies due to the high solubility of natrocarbonatite lava in aqueous solutions.

The corrosion of thermonatrite at the margins of the fringes implies dissolution in a vapour that becomes richer in H₂O with cooling, presumably because magmatic CO₂ becomes depleted as the interior of the flow solidifies and degasses. Under these conditions the halide masses crystallised in voids in the fringe structure. At temperatures less than \( \sim 400^\circ C \) the solubility of NaCl in steam decreases sharply with temperature to less than 0.01 wt\% (Pitzer and Pabalan, 1986). Once the temperature of fumarole gases at the flow top falls below this value, halite precipitation from the vapour will occur rapidly. The observation that the final precipitates are mixed halite and sylvite is difficult to explain in the absence of data on the solubility of KCl in steam but could be explained if decreased KCl solubility in the vapour occurs at somewhat lower temperatures than NaCl.

The alteration of natrocarbonatite lava observed adjacent to cooling cracks suggests that the source of the alkalies and halides in the fumarole gases is gregoryite and sylvite crystals within the fumarole gases. The alteration associated with the dissolution of the most soluble phases in the natrocarbonatite lavas by percolating steam generated from meteoric waters occurs contemporaneously with cooling of the lava and is particularly intense for the thin white tongues at the margins of natrocarbonatite flows. Alteration during the wet season is accelerated compared with the previous dry season estimates (Nyamweru, 1997). Criteria used for estimating the age of lava flows from photographs will thus change depending on the season.

The alteration of the natrocarbonatite lavas adjacent to cooling cracks reported in the present study contrasts with that described for older altered natrocarbonatites (Dawson, 1993; Dawson et al., 1987). Although sylvite is absent in both cases, presumably due to dissolution by aqueous fluids, gregoryite microphenocrysts survive in the latter but are almost completely dissolved adjacent to fumaroles. No alteration of nyerereite to pirssonite or gaylussite (Na₂Ca₂(CO₃)₂·2H₂O), as described in the older lavas, was observed in the current samples in which nyerereite laths remain relatively pristine. The growth of crystallographically controlled aphthitalite within relict gregoryites suggests epitaxial nucleation and growth on nyerereite exsolution lamellae within the gregoryite. The role of exsolution structures in alkali carbonates could be important in the formation of pseudomorphs of gregoryite by other phases such as calcite.

The crystallisation sequence of the salt fringes has implications for the interaction of natrocarbonatite lavas and meteoric water in shallow sub-volcanic

9. Implications

Salt fringes dissolve leaving no residue in deionised water and are thus removed in the first rainfall after their eruption. Since the formation of salt fringes only occurs in the wet season due to the occurrence of water-saturated lavas in the crater they are thus likely to be removed within hours or days of their formation and hence are probably not preserved in the geological record. Despite their transient nature, salt fringes do have implications for the geochemical budget of runoff waters, the alteration of natrocarbonatite lava and the nature of fumarole gases generated at shallow depths by interaction of natrocarbonatite magmas and ground water.

The presence of highly soluble salts on fresh lava flows is likely to provide an important source of solutes for runoff waters flowing from Oldoinyo Lengai in the wet season. Heavy rainfall during the wet season produces flash floods which drain rapidly from the volcanic edifice into the braided streams that dominate the topography of the rift floor to the north of Oldoinyo Lengai. These flow directly into lake Natron increasing the level of the lake and decreasing its salinity. The dissolved alkalies present in runoff from Oldoinyo Lengai minimise the changes in salinity and probably dominate the seasonal flux of alkali that enter the lake.

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The crystallisation sequence of the salt fringes has implications for the interaction of natrocarbonatite lavas and meteoric water in shallow sub-volcanic
environments. The observation that at the highest temperatures only Na-carbonates are deposited from vapours may suggest that at magmatic temperatures interactions between natrocarbonatite magma and ground water lead to Na-rich H₂O–CO₂ coexisting fluids. The removal of Na into the coexisting fluid will cause complementary increases in the Ca/Na and K/Na of the magma.

10. Conclusions

Observations of summit crater eruptions of natrocarbonatite lavas during the wet season reveal that the style of alteration of these hygroscopic materials changes in the presence of meteoric water. Leaching by H₂O-dominated gas generated by vaporisation of ground water results in the dissolution of sylvite and gregoryite in lavas soon after their crystallisation from the melt leaving void spaces. Sublimation of sylvite, halite and aphthitalite from vapours in the matrix and relict phenocrysts of the lavas also occurs. Salt deposits, dominated by thermonatrite, adorn the margins of cooling cracks and have mineralogies that suggest that both magmatic gases and gases generated from meteoric water are involved in their formation. Although these salt fringes are a distinctive feature of natrocarbonatite lavas erupted during the wet season they are transient since they are easily removed by further rainfall and thus are unlikely to be preserved in the geological record.

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References


