UNIVERSITAT DE BARCELONA

Caracterización del vulcanismo carbonatítico de Catanda (Angola)

Marc Campeny Crego

Publicaciones originales

9.1. Publicación I

Campeny M., Mangas J., Melgarejo J.C., Bambi A., Alfonso P., Gernon T., Manuel J. (2014): The Catanda extrusive carbonatites (Kwanza Sul, Angola): an example of explosive carbonatitic volcanism. Bulletin of Volcanology 76, 818-833.

Bull Volcanol (2014) 76:818
DOI 10.1007/s00445-014-0818-6

RESEARCH ARTICLE

The Catanda extrusive carbonatites (Kwanza Sul, Angola): an example of explosive carbonatitic volcanism

Marc Campeny · José Mangas · Joan C. Melgarejo · Aurora Bambi · Pura Alfonso · Thomas Gernon · José Manuel

Received: 5 October 2013 / Accepted: 12 March 2014

Abstract Carbonatite lavas and pyroclastic rocks are exposed in the volcanic graben of Catanda and represent the only known example of extrusive carbonatites in Angola. A new detailed geological map of the area is presented in this study as well as six different stratigraphic sections. Pyroclastic rocks, apparently unwelded, are dominant in the area and represented in all the stratigraphic columns. They form shallowly to moderately inclined layers, mostly devoid of internal structures, that range in thickness from several centimetres to metres. They are dominantly lapilli tuffs and minor tuffs occasionally comprising pelletal lapilli. Based on their different features and field relationships, at least five different pyroclastic lithofacies have been distinguished in the area. Carbonatitic lavas outcrop in the external parts of the Catanda graben, forming coherent layers interbedded with pyroclastic rocks. Calcite is the most common mineral in the lavas, but other accessory minerals such as fluorapatite, titaniferous magnetite, phlogopite, pyrochlore, baddeleyite, monticellite, perovskite, cuspidine and periclase have also been identified. At least four different types of lavas have been distinguished based on their mineral associations and textural features. This study reveals an overall abundance of pyroclastic material in comparison to lava flows in the Catanda area, suggesting that eruptive processes were dominated by explosive activity similar to what has been described in other carbonatite and kimberlite localities. The Catanda carbonatitic volcanism was associated with monogenetic volcanic edifices with tuff ring or maar morphologies, and at least seven possible eruptive centres have been identified in the area.

Keywords Extrusive carbonatite · Carbonatite lava · Carbonatitic lapilli tuff · Angola · Catanda

Editorial responsibility: P-S Ross

M. Campeny (✉) · J. C. Melgarejo
Departament de Cristal·lografia, Mineralogia i Dipòsits Minerals, Universitat de Barcelona, Barcelona, Catalonia, Spain
e-mail: mcampeny@ub.edu

J. Mangas
Departamento de Física, Instituto de Oceanografía y Cambio Global, Universidad de Las Palmas de Gran Canaria, Las Palmas de Gran Canaria, Spain

A. Bambi · J. Manuel
Departamento de Geologia, Universidade Agostinho Neto, Luanda, Angola

P. Alfonso
Departament d'Enginyeria Minera i Recursos Naturals, Universitat Politècnica de Catalunya, Manresa, Catalonia, Spain

T. Gernon
Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton Waterfront Campus, Southampton, UK

Introduction

The study of extrusive carbonatites, and in particular carbonatitic lavas, is important for developing a better understanding of eruptive processes of low viscosity melts (i.e. 1–120 Pa.s; Dawson et al. 1995) and the distribution of chemical elements in carbonatitic magmas. The characterization of extrusive products provides important information that is not revealed by intrusive rocks, and it can also be essential to understand the results obtained by experimental petrology (e.g. Bailey 1993). Woolley and Church (2005) reported over 40 extrusive carbonatite localities in the world, but lava flows are described in only 14 of those. Carbonatitic lavas and pyroclastic rocks are exposed in the volcanic province of Catanda, representing the only extrusive carbonatites in Angola (Woolley 2001).

Catanda is located in the Kwanza Sul Province, around 350 km SE from Luanda and 90 km SE from the town of

Published online: 28 March 2014

Sumbe (Fig. 1). These carbonatite outcrops were last described by Gomes (1971) and Silva and Pereira (1973), but for more than 30 years, the Angolan civil war prevented more systematic studies. Due to an abundance of landmines in the Catanda area, some of the best outcrops are still inaccessible.

This contribution provides a new detailed geological study of the Catanda extrusive carbonatites, describing the stratigraphic relationships, and petrographic and mineralogical features of both pyroclastic rocks and lavas. The principal aim of the study is to reconstruct the preexisting morphology of volcanic edifices and interpret the key eruptive processes occurring in Catanda.

Geological setting

Lucapa corridor

The Catanda extrusive carbonatites occur within the Lucapa corridor (Fig. 2)—a 300-km-long NE–SW-oriented rift in the Congo-Kassai craton, developed during the Early Cretaceous and related to the opening of the Atlantic Ocean (Sykes 1978; de Boorder 1982). Most of the Angolan carbonatites and kimberlites are spatially associated with this structure (Issa Filho et al. 1991). While the majority of kimberlites are restricted to the NE of the structure (Fig. 2), most of the carbonatites are located in the central and SW regions of the Lucapa corridor (Lapido-Loureiro 1968, 1973; Alberti et al. 1999). The spatial and temporal relationship between carbonatites and kimberlites in the Lucapa corridor is still poorly understood. The age of the Catoca kimberlite, considered to be the fourth largest kimberlite pipe in the world and located in the NE part of the Lucapa corridor, was reported by Robles-Cruz et al. (2012) using zircon U-Pb geochronology as 117.9±0.7 Ma. Other reported ages for Lucapa kimberlites are Val do Queve at 133.4±11.5 Ma (Haggerty et al. 1983) and the Luxinga kimberlite cluster where the age of pipes ranges from 145 to 113 Ma (Eley et al. 2008). Jelsma et al. (2012) recently reported ages from 252 to 216 Ma for central Angolan kimberlite pipes using zircon U-Pb geochronology. The main intrusive Angolan carbonatitic complexes such as Tchivira (Melgarejo et al. 2012) or Virulundo (Torró et al. 2012) have yet to be dated. Nevertheless, they are considered to be related to the Lucapa structure and broadly contemporaneous with the intrusion of kimberlitic clusters in the area.

Catanda region

The Catanda extrusive carbonatites outcrop in a 50-km^2 graben hosted in Archean granites and delimited by the intersection of three principal fault systems with ENE–WSW, NNW–SSE and WNW–ESE alignments (Fig. 3). These faults are also responsible for feeding active geothermal systems (thermal springs) and forming travertine deposits up to 10 m in thickness. Given the absence of outcropping limestone or other sedimentary rocks, the travertine deposits are likely related to the chemical remobilization of carbonatitic volcanic rocks.

Carbonatitic outcrops consist of small groups of eroded hills largely covered by colluvial sediments produced by rock weathering, and by alluvial sandy detrital sediments, which partly obscure the position of the original eruptive centres (Fig. 4a, b).

The age of Catanda volcanism has not been precisely determined: Silva and Pereira (1973) proposed an approximate age of 92±7 Ma for a tinguaite dyke apparently contemporary with the carbonatites; however, the dating method employed was not specified.

Methodology

During the fieldwork, six stratigraphic columns were measured at 1:100 scale. Some 58 samples collected in 2011 are discussed here (the 2013 samples have not yet been analysed). Optical microscopy was used for mineral identification and observing the main textural features of samples. Scanning electron microscope E-SEM Quanta200 FEI XTE 325/D8395BSE with a Genesis EDS microanalysis system from the Scientific and Technical Centres of the University of Barcelona (CCiTUB) was also used to describe in detail the key mineralogical relationships and textures. The operating conditions of the SEM were 20–25 keV, 1 nA beam current and 10 mm of distance between sample and detector.

General description of outcrops

The measured Catanda volcanic sections have a thickness of up to 50 m, although the highest relief is formed by the hills of Gojomba (Fig. 3) that have an altitude difference (top to base) of approximately 100 m. The sections are composed dominantly of pyroclastic beds, but minor lava flows were identified in some outcrops located in external parts of the graben (Fig. 3: stars; e.g. Fig. 4c–e).

Pyroclastic rocks

Pyroclastic rocks are represented in all studied stratigraphic sections, where they form extensive layers ranging in thickness from several centimetres (Fig. 5a) to metres but typically 10–40 cm thick. Resedimentation processes are not considered important in the formation of these rocks, which are interpreted as pyroclastic based on the shapes of the inferred volcanic edifices (see below) and the absence of sedimentary structures such as erosive surfaces, fluvial channels and clast

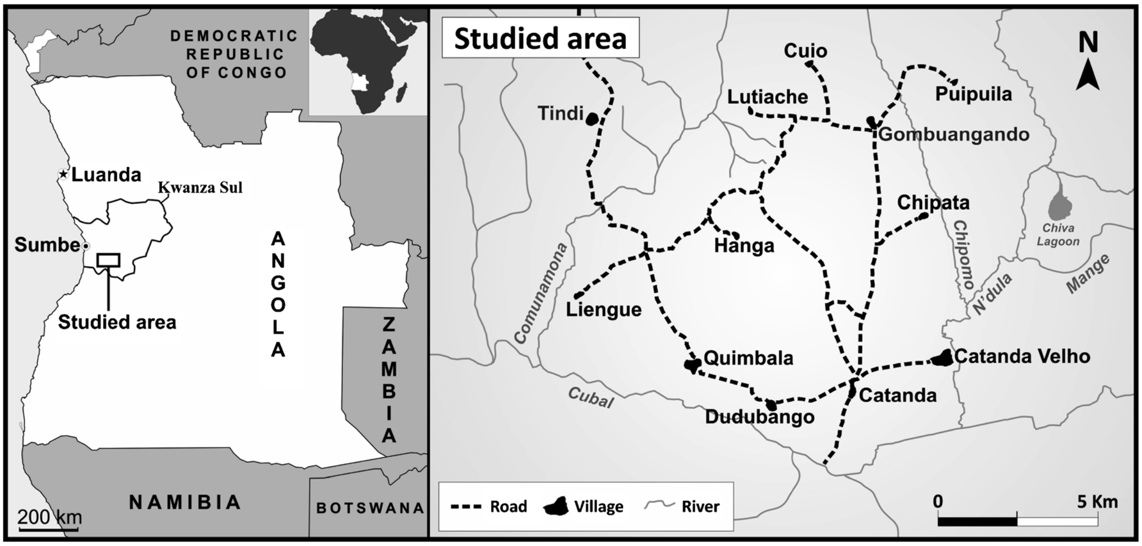

Fig. 1 **a** Location of the studied area in the Kwanza Sul county of Angola. **b** Detailed map of the studied area showing the location of Catanda and other significant localities

imbrications within the beds. The pyroclastic strata exhibit shallow to moderate inclinations, typically ranging from 10° to 15°. The beds are mostly devoid of internal structures but occasional display low-angle cross-bedding (Fig. 5b) and inverse grading (Fig. 5c). The rocks are apparently unwelded and exhibit abundant localised joints (cracks) and veins filled by secondary sparitic calcite. Pyroclast diameter is mainly between 2 and 16 mm, forming fine and medium lapilli tuffs

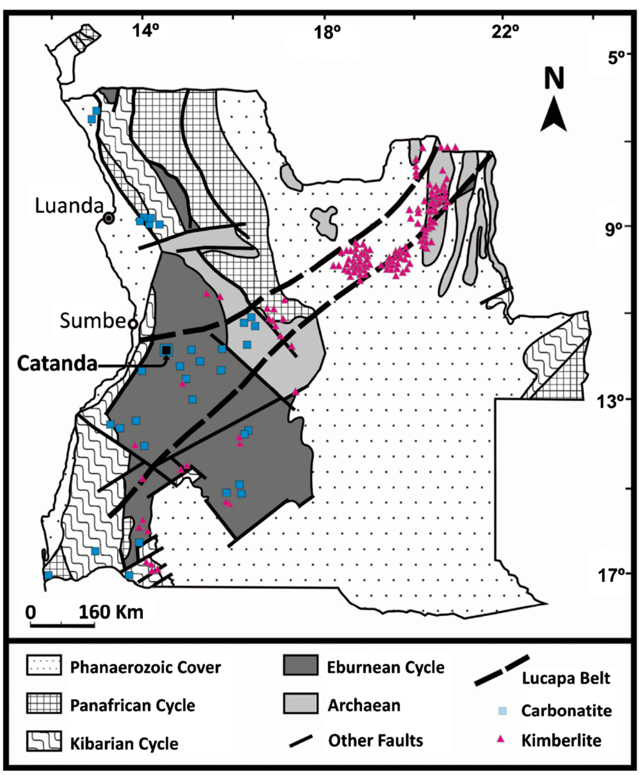

Fig. 2 Simplified geological map of Angola and the Lucapa structure showing the location of reported Angolan carbonatites and kimberlites

(White and Houghton 2006) occasionally comprising pelletal lapilli[1] and crystals up to 1 cm in diameter (Fig. 5d). In some sequences, tuffs (defined as having >75 % ash-sized particles) are also present as relatively thin layers (<15 cm thick). Juvenile components (carbonatite fragments and related free crystals) make up 40–75 % of the macroscopically visible fragments, whereas lithic clasts and related free crystals represent 25–60 % (Table 1). The lithic fraction is dominated by Archean granitic clasts and related free crystals (95 %) ranging in diameter from 3 to 10 cm for the granite clasts (exceptionally up to 30 cm) with minor amphibolite (4 %) and plutonic carbonatite clasts (1 %). Granite concentrations occasionally form horizons of coarse lapilli tuff and block-rich lapilli tuff (Table 1). On the basis of grain size (tuff to lapilli tuff), sorting (good to poor), clast shapes (very low to high angularity) and componentry, we distinguish five pyroclastic lithofacies in the Catanda outcrops (Fig. 6 and Table 1).

Lavas

Carbonatite lavas outcrop in distal regions of the SE part of the Catanda graben (Fig. 3). They exhibit a very distinctive morphology and texture compared to pyroclastic lithofacies, forming homogeneous and coherent bodies with no discernible internal structures. These bodies are up to 7 m thick (Fig. 5e) and are typically interbedded with pyroclastic strata. Lava flows lack scoria horizons and contain irregular secondary joints. They range in colour from dark grey to brown and generally exhibit finely porphyritic textures. Rock fragments

[1] Pelletal lapilli are defined as spherical to elliptical lapilli commonly with a crystal fragment or a lithic clast in the centre, mantled by fine-grained micro-phenocrystal material that sometimes defines smooth concentric layers (Mitchell 1997).

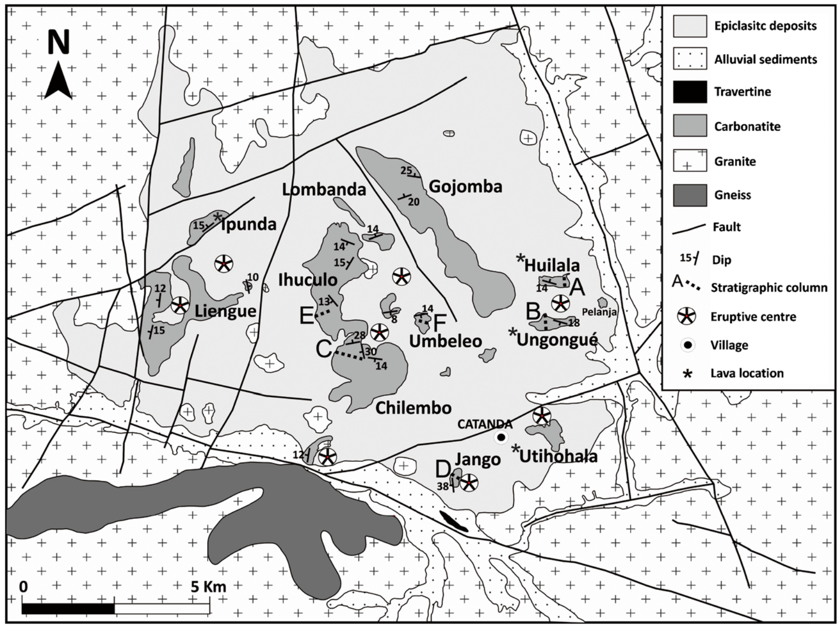

Fig. 3 Geological map of the Catanda carbonatitic area showing locations of the main extrusive carbonatite outcrops (same area as Fig. 1b). The location of the six stratigraphic sections constructed in this study (see Fig. 7) are shown, as well as the interpreted eruptive centres (see "Discussion" section)

are widespread (3–5 %) in practically all lava flows, and these range in diameter from 5 to 50 cm. The composition of these rock fragments is mainly granitic (Fig. 5f), but some mafic and plutonic carbonatite clasts can also be found. Although the lavas contain granitic clasts, these are more abundant in the pyroclastic rocks, in which they form discrete layers.

Volcanic stratigraphy

We describe six stratigraphic columns (Fig. 7) constructed in different parts of the Catanda graben (Fig. 3).

Huilala (A)

The Huilala section (Fig. 7a) is approximately 27 m thick and was measured on the northern slope of Huilala hill, located in the SW area of the Catanda graben (Fig. 3). Four lapilli tuff horizons in part covered by epiclastic materials form the lower part of the section (0–17 m). These horizons are moderately sorted to well sorted and range in thickness from 1 to 4 m. They consist of carbonate ash supporting angularly and irregularly shaped centimetre-scale juvenile-free crystals of titaniferous magnetite and phlogopite as well as lithic grains coming from the Archean granites such as quartz, microcline and plagioclase. In addition, disseminated granitic blocks up to 20 cm in diameter are scattered in these horizons. In general, structures such as cross-bedding are not present in these beds, although cryptic layering is locally developed in the lower levels. At Huilala, the following pyroclastic lithofacies are observed: 3, 4 and 5 (Table 1).

Lavas form dark grey coherent aphanitic bodies in the upper part of the section (17–27 m; see Fig. 7) generating a topographic high. Lava outcrops are isolated and discontinuous, so the presence of several flows cannot be ruled out. It is not possible to distinguish flow-related structures, but horizontal as well as minor vertical cooling joints are common (Fig. 5e). Granitic fragments up to 30 cm long are incorporated into the lava as well as fragments of aphanitic whitish rocks up to few centimetres in diameter, which likely represent highly altered volcanic material.

Ungongué (B)

Ungongué is an elongated hill located in front of Huilala, in the SW part of the Catanda area (Fig. 3). The Ungongué section is approximately 51 m thick and was measured on the southern slope of the hill. The section consisted of intercalated lavas and pyroclastic layers, partly covered by epiclastic deposits (Fig. 7b). The pyroclastic rocks can be classified as lapilli tuffs, containing some granitic and mafic (aphyric) lithic blocks up to 15 cm diameter at all levels. Interstitial spaces (unfilled porosity) from 0.2 to 0.5 mm diameter can be distinguished, particularly in the upper pyroclastic layers. At Ungongué, only one pyroclastic lithofacies is observed (Table 1, number 5).

Ungongué lavas share many similarities with the Huilala flows. Three lava flows can be distinguished in the lower part and two thicker flows in the middle upper part of the section. In the upper lava flows, we note a greater presence of granitic and mafic aphyric rock fragments up to 20 cm in

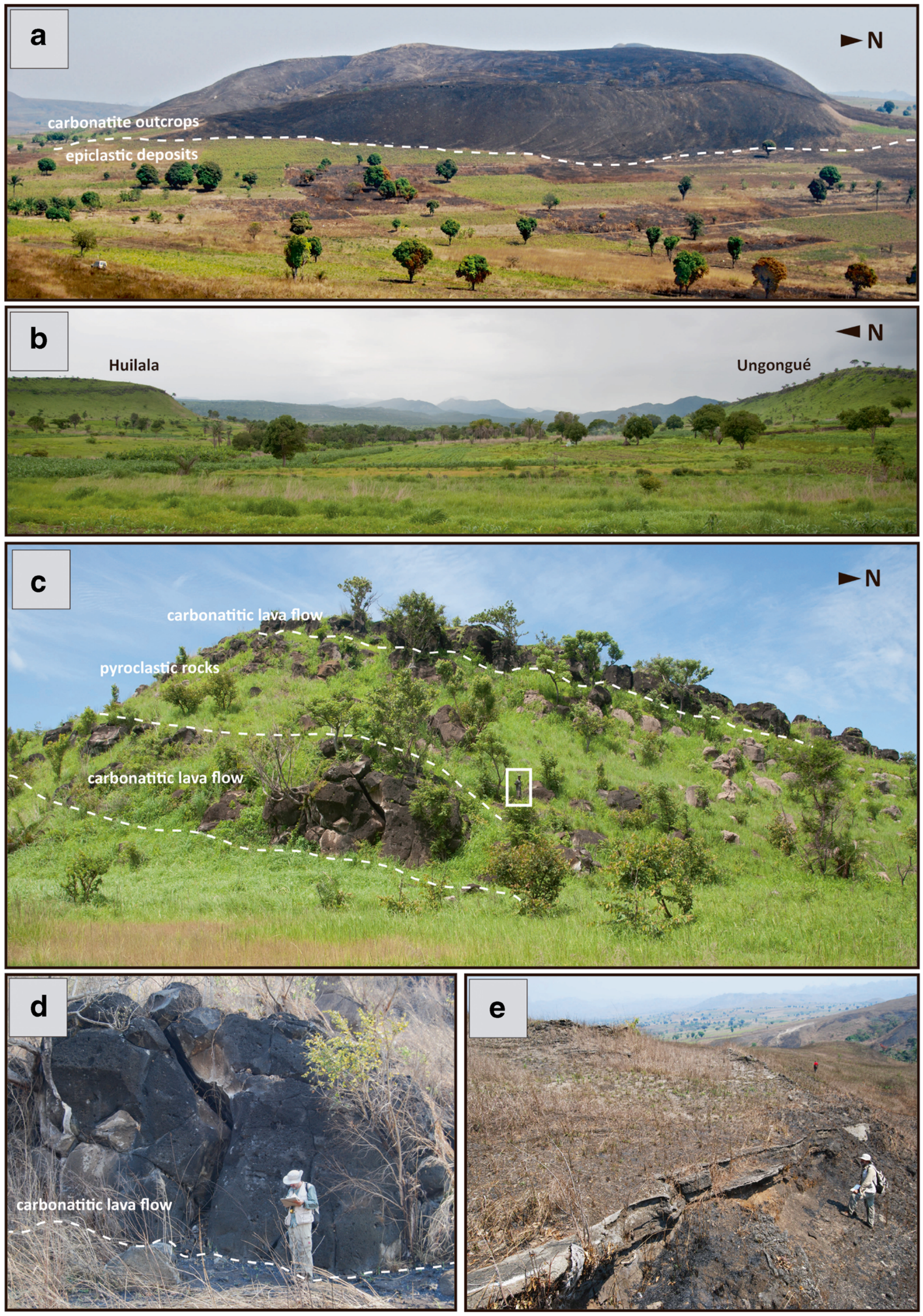

Fig. 4 **a** View of the Gojomba carbonatitic edifice outcropping in the Catanda graben, mainly covered by epiclastic materials. **b** General view of the Huilala and Ungongué hills defining the position of the ancient eruptive centre (possible crater) in the middle of the area. **c** General view of the Jango outcrops in which it is possible to distinguish carbonatite pyroclastic deposits and lavas (see person inside *square* for scale). **d** Carbonatite lava flow outcropping in the lower part of the Jango section. **e** Lapilli tuffs in the Chilembo area

diameter. Considering their position in the stratigraphic sequence, dip angle and mineralogical and textural features, the upper levels of the Ungongué lavas are correlated with the upper lava flows of the Huilala section. On the basis of bed correlations, dip direction and the position and morphological features of the outcrops, they can be considered to belong to the same monogenetic volcano, about 800 m in diameter, with a proposed eruptive centre between Huilala and Ungongué (Fig. 3).

Chilembo (C)

Chilembo is a rounded hill located in the southern part of the Catanda area (Fig. 3). We measured a 41-m-thick section (Fig. 7c) on the NW slope, where outcrops are more extensive and not covered by colluvial epiclastic sediments. Carbonatite lavas are not present in Chilembo: the section consists exclusively of pyroclastic rocks. Pyroclastic beds are thinner (ranging from 10 to 50 cm) than in the Huilala and Ungongué

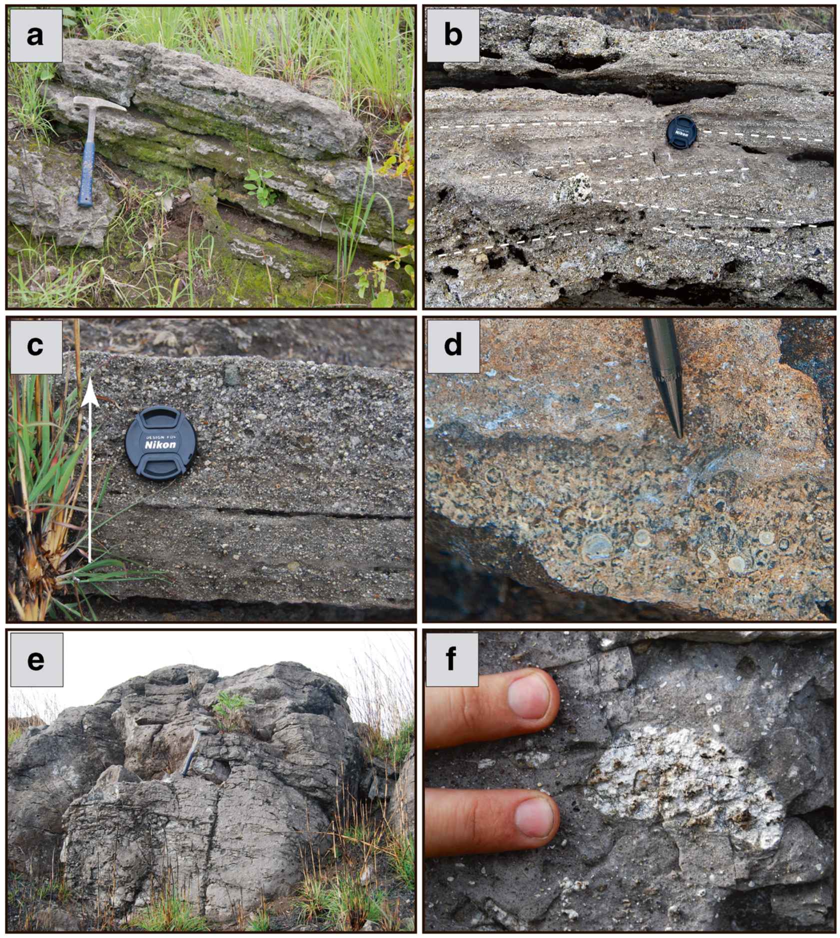

Fig. 5 **a** Laminated pyroclastic layers in the Gojomba area (see Fig. 3). **b** Cross-bedding in lapilli tuffs from the upper part of Umbeleo section. **c** Reverse grading in lapilli tuffs from the Ihuculo section. The upper part of the layer is enriched in quartz, plagioclase and microcline derived from the host granites. **d** Pelletal lapilli tuff layer from the Quimbala area (see Fig. 3). **e** Coherent lava flow in the upper part of the Huilala section. **f** Lithic fragment (granite) incorporated into the lavas of the Ungongué area

sequences, and these are dominantly lapilli tuffs with subordinate tuffs. Layering is extensive but particularly well developed in the lower and middle levels of the section. In the upper part, some tuff beds are enriched in pelletal lapilli up to 1 cm in diameter with concentric internal structures. At Chilembo lithofacies, 1, 3, 4 and 5 are observed (Table 1).

Jango (D)

The Jango edifice is an isolated carbonatite outcrop located in the SE part of the graben, very close to Catanda village (Fig. 3). The section is approximately 22 m thick (Fig. 7d). Jango is the only locality at Catanda where lava flows predominate over pyroclastics rocks.

Pyroclastic rocks are concentrated in the middle of the sequence, forming lapilli tuffs enriched in country rock fragments and characterised by well-developed plane parallel layering. The rocks are also permeated by 3–5-cm-thick secondary cracks filled by sparitic calcite. At Jango, the only pyroclastic lithofacies that is observed is number 4 (Table 1).

Jango lava flows are present in the upper and lower levels of the section, and they have a very different appearance relative to the Huilala-Ungongué lavas. Jango lavas are aphyric black rocks rich in vesicles up to 1 cm in diameter, infilled by fibrous secondary minerals and sparitic calcite (Fig. 8d). Country rock fragments of granitic and mafic composition up to 15 cm in diameter are abundant at both levels. As in the middle pyroclastic level, secondary cracks infilled by sparitic calcite are developed in the lavas, especially at upper levels in the section.

Ihuculo (E)

Ihuculo is an elongated hill located in the central part of the Catanda graben. A partially exposed 16-m section was measured on the western slope where some pyroclastic layers outcrop between the colluvial epiclastic sediments (Fig. 7e). Lava flows were not recorded.

Pyroclastic rocks are mostly lapilli tuffs containing granitic and mafic volcanic fragments up to 15 cm in the lower part of the section and smaller (between 2 and 5 cm) in the upper levels, defining crude normal grading.

Table 1 Summarised description and interpretation of pyroclastic lithofacies in the Catanda area. See images in Fig. 6

Pyroclastics facies	Description	Explosivity
1. Medium-coarse tuff	Description: brown tuff consisting of a majority of ash components (1/4 to 1 mm) and a very small proportion of granitic fragments	High
	Structure: not bedded	
	Grain size: 80–90 % ash; 10–20 % lapilli	
	Sorting: well sorted	
	Clast shape: rounded, low angularity	
	Lithic fragments: ≈5 area %	
2. Pelletal lapilli-rich tuff	Description: matrix-supported lapilli tuff comprising pelletal grains (≤1 cm). Cement consists of secondary interstitial calcite. Pelletal lapilli cores are composed of different minerals such as quartz, plagioclase, feldspar, augite, calcite or apatite	Moderate–high
	Structure: not bedded	
	Grain size: 60–70 % ash; 30–40 % lapilli	
	Sorting: moderately sorted	
	Clast shape: rounded, very low angularity	
	Lithic fragments: ≈25 area %	
3. Lapilli tuff	Description: matrix-supported lapilli tuff formed by angular and irregular rock fragments of quartz, feldspar, plagioclase, magnetite and phlogopite. Cement is composed of secondary interstitial calcite	Moderate
	Structure: not bedded	
	Grain size: 30–40 % ash; 60–70 % lapilli	
	Sorting: moderately sorted	
	Clast shape: moderate angularity	
	Lithic fragments: ≈50 area %	
4. Bedded lapilli tuff	Description: bedded lapilli tuff composed of rounded granitic rock fragments, magnetite, phlogopite and pyroxene. Interstitial calcite, mantle xenoliths (≈5 vol%)	Variable
	Structure: thin bedded (1–3 cm)	
	Grain size: 30–40 % ash; 60–70 % lapilli	
	Sorting: well sorted	
	Clast shape: moderate angularity	
	Lithic fragments: ≈60 area %	
5. Block-rich lapilli tuff	Description: lapilli tuff with significant granitic and mafic blocks up to 10 cm in diameter. Secondary sparitic calcite filling interstitial spaces	Low
	Structure: not bedded	
	Grain size: 30–40 % ash; 50–55 % lapilli; 10–15 % blocks	
	Sorting: poorly sorted	
	Clast shape: moderate–high angularity	
	Lithic fragments: ≈60 area %	

Layering is widely present in almost all beds, especially in the upper levels, where it is possible to distinguish inverse grading. At Ihuculo, lithofacies 2, 3, 4 and 5 are observed (Table 1).

Umbeleo (F)

Umbeleo is a small rounded hill located in the central eastern part of the graben. Colluvial sediments cover most of the outcrop; however, some pyroclastic levels can be distinguished especially in the upper part of the section (Fig. 7f). No lavas were observed. Pyroclastic rocks are dominated by lapilli tuffs rich in country rock lithics. One of the most distinctive features is the presence of cross-bedding (Fig. 5b), as well as inverse grading (Fig. 5c). The tuffs contain thin layers (up to 1–2 cm thick), in which small lithic fragments define cross-bedding. Fluvial sedimentary structures such as channels or erosion surfaces are not distinguished in these beds, which suggests that the cross-bedding is more likely related to pyroclastic surges. At Umbeleo, all five lithofacies are observed (Table 1).

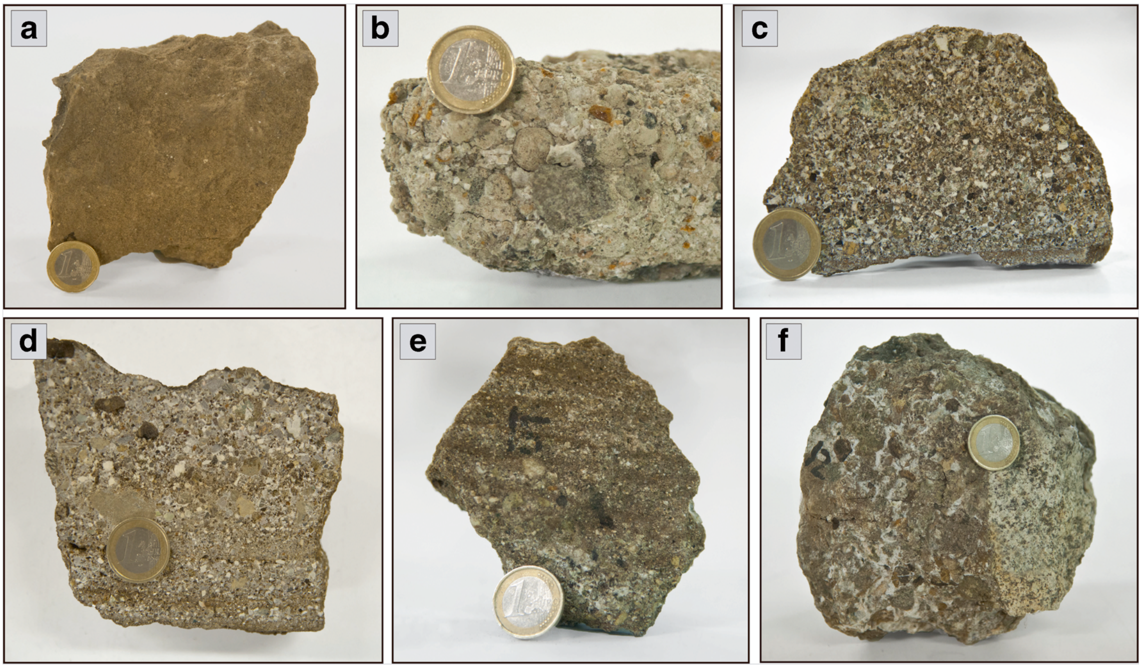

Fig. 6 Images of pyroclastic facies described in Table 1. **a** Brown carbonatitic tuff. **b** Pelletal lapilli tuff. **c** Lapilli tuff composed of angular and irregular rock fragments. **d** Bedded lapilli tuff composed of angular rock fragments. **e** Bedded lapilli tuff consisting of small lapilli. **f** Block-rich lapilli tuff in which is possible to distinguish a ~9-cm granitic fragment

Petrography

Pyroclastic rocks

In general, the mineral assemblage of pyroclastic rocks is uniform across exposures in Catanda. Under the microscope, the pyroclastic rocks consist of juvenile carbonatite fragments (5–10 %), free crystals derived from the carbonatite magma (10–15 %), lithic rock fragments (5–10 %) and related free crystals (15–20 %), a fine-grained (tuffaceous) calcite matrix (20–25 %) and cement formed by sparitic calcite (15–20 %). These components are now described in turn.

The juvenile carbonatite fragments mostly consist of spherical grains up to 1 cm in diameter. They can present a concentric pelletal structure sometimes developed around precursor grains that include sparitic calcite, titaniferous magnetite (Fig. 8a, b) or augite, as well as crystals from the Archean granites, in particular quartz (Fig. 8c). In the Ipunda area, several pyroclastic levels, interbedded with lava flows, comprise spherical juvenile fragments that contain euhedral tabular calcite crystals defining a well-developed trachytoid texture (Fig. 8d). Discrete vesicles commonly coalesced and up to 2 mm in diameter are also common inside these spherical grains (Fig. 8e). Similar trachytoid textures in spherical lapilli have been described in the Rockeskyll complex (Keller 1981; Riley et al. 1996).

Free crystals derived from the carbonatite magma are mostly formed by calcite as well as fluorapatite occurring as subhedral and prismatic crystals up to 0.5 mm long. Other accessory minerals such as euhedral titaniferous magnetite grains, pyrochlore, baddeleyite (Peres and Gomes 1969), strongly zoned augite and phlogopite also occur.

Country rock lithics are also common in pyroclastic rocks. Petrographically, these are dominated by grains derived from Archean granites (~75 % of the lithic population), mainly quartz and microcline. Amphibolite and pyroxenite fragments are present in lower quantities (~25 % of the lithic population) as well as rare rounded grains of glimmerite (micaceous xenoliths related to mantle metasomatism; Fig. 8f) also described in other carbonatite localities such as Polino (Stoppa and Lupini 1993).

Grain shapes are generally angular or moderately angular except in the tuff and pelletal lapilli-rich facies in which clasts are round to sub-angular (Table 1).

Cement is widely present in the entire pyroclastic facies infilling cracks and interstitial space. It is mainly made of sparitic calcite crystals up to 0.5 cm.

Lavas

In the Catanda region, four different types of carbonatite lavas located in different eruptive centres can be distinguished based on their mineralogical and textural features (Table 2 and Fig. 9).

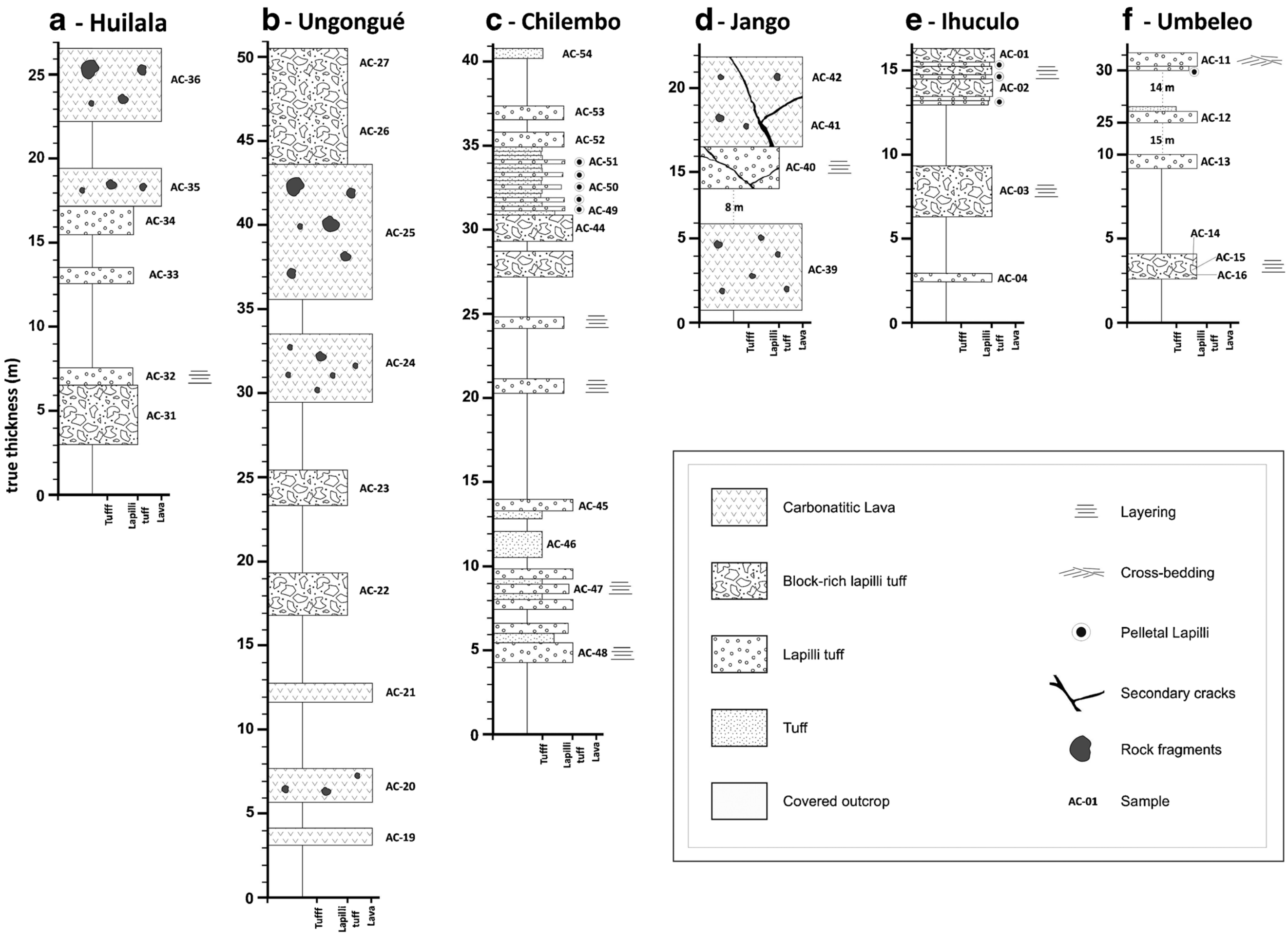

Fig. 7 Stratigraphic sections of the Catanda volcanic carbonatites. The location of each section is shown on the geological map (Fig. 3)

Huilala-Ungongué

The Huilala-Ungongué lavas outcrop in the SE part of the Catanda graben in three different nearby hills: Huilala to the north, Ungongué to the south and Pelanja to the east (Fig. 3). The lavas are dark grey with a finely porphyritic texture (Fig. 9a) and have a relatively low percentage of carbonates (approximately 30 vol%). Phenocrysts make up 25–30 % of the samples by surface area. Within the phenocryst population, we observe 30–35 % typically euhedral zoned apatite up to 1 mm across; 25–30 % strongly zoned grains of titaniferous magnetite up to 0.5 mm in diameter with inclusions of pyrite and pyrrhotite; 10–15 % subhedral phlogopite up to 2 mm long; 10–15 % strongly zoned euhedral augite up to 1 mm long; and 0–5 % altered subhedral grains of olivine up to 1 mm (c.f. Peres et al. 1968). The groundmass mainly consists of fine-grained calcite and accessory minerals such as apatite, titaniferous magnetite, pyrochlore, baddeleyite, zirconolite, perovskite, monticellite and cuspidine. Brucite is also present, typically forming alteration halos around primary grains of periclase that are sometimes still preserved (Fig. 10a). Sparitic secondary calcite is also present infilling vesicles (≈5 vol%) up to 3 mm in diameter. Granitic fragments and minerals derived from the Archean granites, such as quartz, microcline and plagioclase, are also recognisable in these lavas representing approximately 5 vol%.

Utihohala

The Utihohala lavas form an isolated flow restricted to a topographic low (Fig. 3). These samples typically have a finely porphyritic texture, with 10–15 % phenocrysts in a carbonate-rich groundmass. Within the phenocryst population, we note 55–60 % euhedral apatite up to 0.5 mm; 15–20 % subhedral phlogopite up to 3 mm; 5–10 % euhedral amphibole up to 1 mm; and 5–10 % zoned augite up to 1 mm in size. The groundmass is calcite-rich but also contains accessory minerals such as apatite (Fig. 9b) and titaniferous magnetite as well as other minor phases such as pyrochlore, baddeleyite, barite and monticellite. Occasional euhedral grains of alabandite about 5 μm in diameter are also present (Fig. 10b). Perovskite, cuspidine and the brucite halos described for the Huilala-Ungongué lavas are not present in Utihohala lavas. Rock fragments up to 4 cm in diameter and

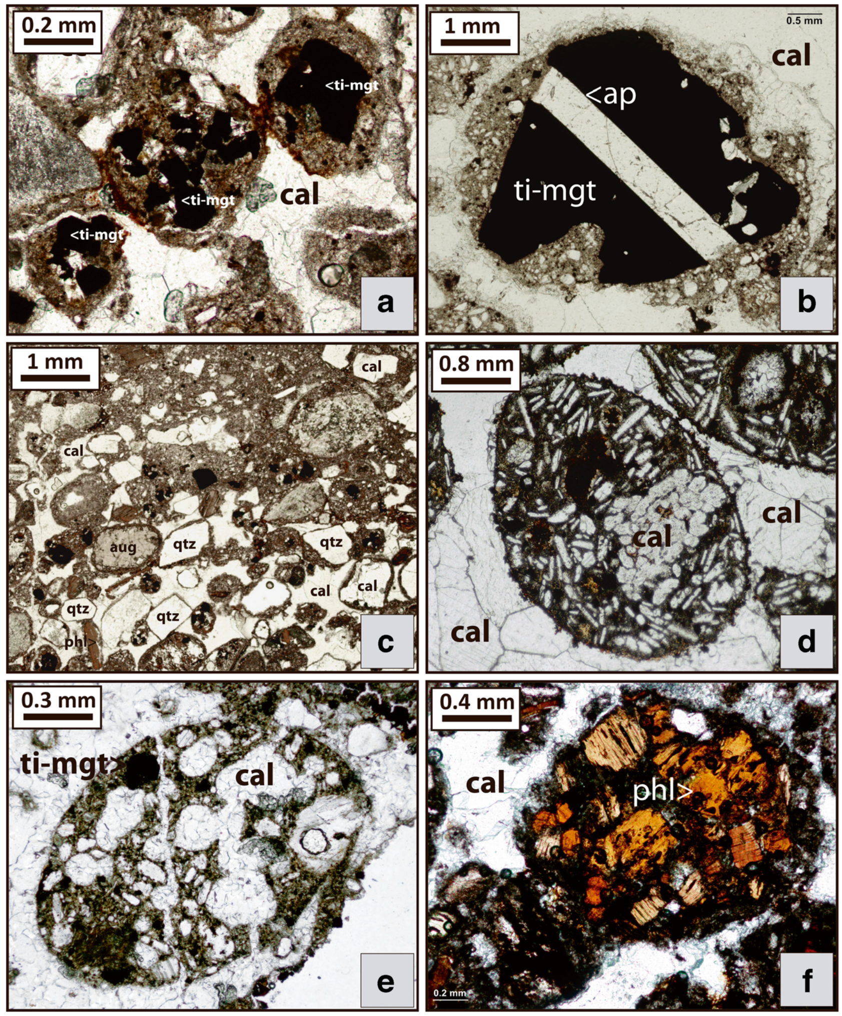

Fig. 8 Plane-polarised light photomicrographs of pyroclastic rocks. **a** Titaniferous magnetite (*ti-mgt*) cores to juvenile fragments. The *top right* fragment shows a pelletal texture. **b** Apatite (*ap*) inclusion inside titaniferous magnetite (*ti-mgt*) grain forming the core of a juvenile fragment. **c** Lapilli tuff from the Lombanda area. Juvenile fragments (ash- and lapilli-sized) contain magma-derived minerals such as calcite (*cal*), augite (*aug*), phlogopite (*phl*) as well as quartz (*qtz*) xenocrysts derived from the granite host rocks. The cement between the pyroclasts consists of sparitic calcite (*cal*). **d** Elliptical, non-vesicular juvenile lapillus comprising tabular calcite (*cal*) crystals showing a trachytoid texture. A coarse-grained carbonatitic inclusion, probably of plutonic origin, is also found inside the lapillus. The cement around the lapillus is sparitic calcite (*cal*). **e** Elliptical vesicular juvenile lapilli from the Ipunda area formed by calcite (*cal*) and other accessory minerals such as titaniferous magnetite (*ti-mgt*). Vesicles are infilled by sparitic calcite. **f** Rounded glimmerite fragment principally formed by phlogopite (*phl*) from a lapilli tuff sample

mineral grains from the Archean granites such as quartz and microcline are also present in these lavas representing around 3 vol%.

Ipunda

The Ipunda lavas contain 75–80 % tabular phenocrysts defining a trachytoid texture (Fig. 9c) similar to that described in the teardrop lapilli of Kirchberg, Germany (Keller 1989) and in Tinderet Hills, Kenya (Deans and Roberts 1984; Zaitsev et al. 2013). Within the phenocryst population, calcite dominates and the other phases are 5–10 % euhedral apatite up to 1 mm long, 5–10 % strongly zoned euhedral titaniferous magnetite up to 2 mm (Fig. 10c), as well as ~5 % euhedral zoned augite grains up to 0.5 mm long. In the groundmass, calcite dominates and accessory minerals such as pyrochlore and baddeleyite as well as phlogopite are present in very minor proportions (less than 5 %) relative to the other lavas described above. Sparitic calcite is very abundant infilling vesicles and secondary cracks. Lithic fragments are very scarce in this type of lavas and represent less than 1 vol%.

Jango

The Jango lava flows are dark brown in colour and exhibit abundant (15–20 %) vesicles typically infilled by secondary sparitic calcite. Overall carbonate content is approximately 70 vol% and is higher than in the other lavas, in particular those at Huilala-Ungongué (in which is approximately 30 vol%). The texture is finely porphyritic with 20–25 % phenocrysts in a fine calcitic groundmass. Within the phenocryst population, there are 65–70 % euhedral grains of apatite up to 1 mm in diameter; 10–15 % phlogopite up to 2 mm; and 10–15 % strongly zoned crystals of titaniferous magnetite up to 2 mm in diameter with well-developed atoll textures. The groundmass mostly consists of fine-grained calcite with sparitic zones infilling small cracks (Fig. 9d). The most common groundmass accessory minerals are apatite, titaniferous magnetite, pyrochlore, baddeleyite and a predominance of

Table 2 Mineralogy of the different carbonatite lavas distinguished in the Catanda area

Mineral	Ideal formula	Huilala-Ungongué			Utihohala			Ipunda			Jango		
		Groundmass	Phenocrysts	Xenocrysts	Groundmass	Phenocrysts	Xenocrysts	Groundmass	Phenocrysts	Xenocrysts	Groundmass	Phenocrysts	Xenocrysts
Calcite	$CaCO_3$	X			X			X	X		X		
Fluorapatite	$Ca_5(PO_4)_3F$	X	X		X	X		X	X		X	X	
Titaniferous magnetite	$Fe^{2+}(Fe^{3+},Ti)_2O_4$	X	X		X	X		X	X		X	X	
Perovskite	$CaTiO_3$	X											
Cuspidine	$Ca_4(Si_2O_7)(F,OH)_2$	X											
Pyrochlore	$(Na,Ca,Pb,U)_2Nb_2(O,OH)_6(OH,F,O)$	X			X			X					
Zirconolite	$CaZrTi_2O_7$	X											
Baddeleyite	ZrO_2	X			X			X					
Alabandite	MnS				X						X		
Periclase	MgO	X											
Monticellite	$CaMgSiO_4$				X						X		
Phlogopite	$KMg_3(AlSi_3O_{10})(OH,F)_2$	X	X		X			X			X		
Augite	$(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$	X	X									X	
Olivine	$(Mg,Fe)_2SiO_4$		X			X							
Quartz	SiO_2			X			X			X			X
Microcline	$KAlSi_3O_8$			X			X			X			X
Plagioclase	$NaAlSi_3O_8$–$CaAl_2Si_2O_8$			X			X			X			X

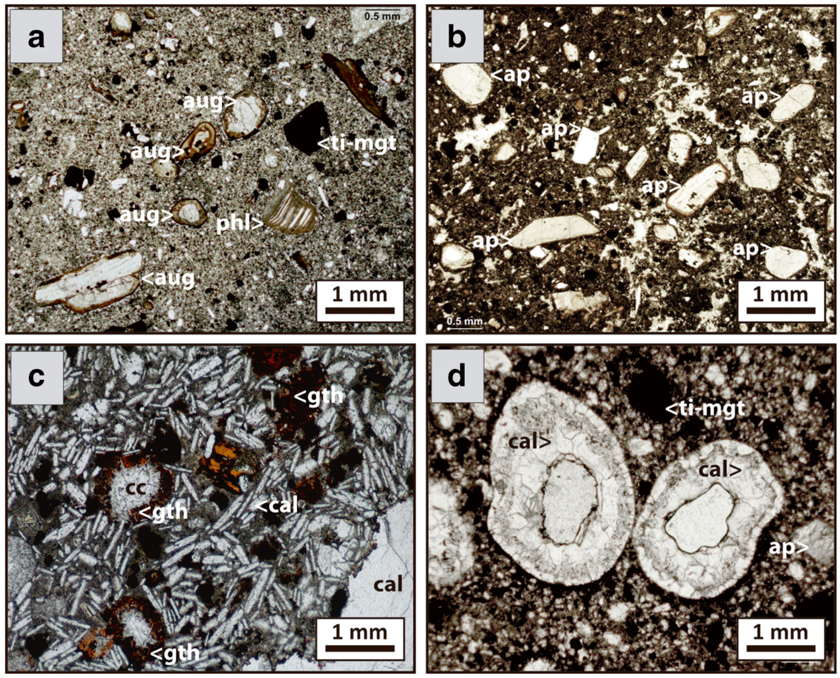

Fig. 9 Plane-polarised light photomicrographs of lavas. **a** Huilala-Ungongué carbonatitic lava in which it is possible to distinguish abundant silicate minerals such as phlogopite (*phl*) and augite (*aug*). **b** Utithohala lava with apatite (*ap*) phenocrysts and calcite groundmass. **c** Typical trachytoid texture of the Ipunda carbonatite lavas formed by aggregates of tabular calcite (*cal*) crystals and secondary goethite (*gth*) filling vesicles and interstices between grains. **d** Appearance of Jango lavas with abundant vesicles infilled by sparitic calcite (*cal*). Apatite (*ap*) and titaniferous magnetite (*ti-mgt*) are also present in the groundmass

monticellite (Fig. 10d), as described in other extrusive carbonatites such as that of Polino, Italy (Stoppa and Lupini 1993). Some typical accessory minerals present in the Huilala-Ungongué lavas such as perovskite, cuspidine and periclase are not observed in the Jango lavas. Granite fragments are very scarce in the Jango lavas (less than 1 vol%).

Discussion

Carbonatites exposed in the Catanda area consist of pyroclastic rocks and lava flows. They form a cluster of small discrete volcanic edifices. Here, we discuss the nature of the eruptive processes responsible for the emplacement of pyroclastic

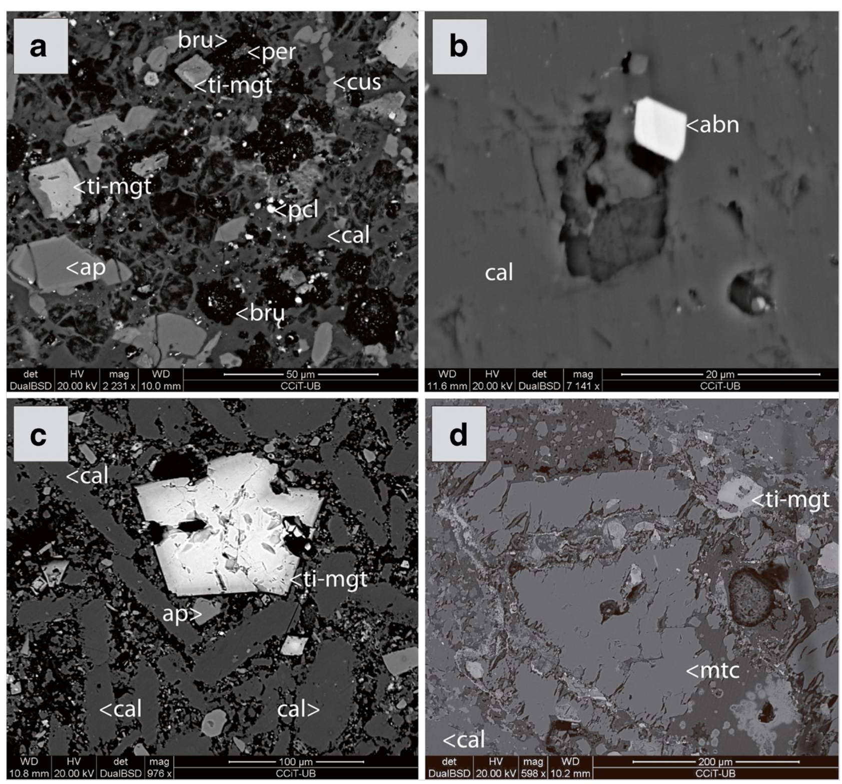

Fig. 10 Backscattered scanning electron microscope (SEM) images of the lavas. **a** Huilala-Ungongué lavas are very rich in accessory minerals such as apatite (*ap*), cuspidine (*cus*) and pyrochlore (*pcl*) as well as brucite (*bru*) that forms typical black drops likely produced by the alteration of periclase (*per*). **b** Alabandite crystal set within primary calcite from a Utithohala lava sample. **c** Tabular calcite (*cal*) crystals and titaniferous magnetite (*ti-mgt*) phenocryst in Ipunda lava sample. **d** Monticellite (*mtc*) grain with calcite (*cal*) matrix and titaniferous magnetite (*ti-mgt*) phenocrysts in Jango carbonatite lava sample

rocks and infer the approximate positions of eruptive centres in the Catanda area. We also interpret the mineralogy, texture and origin of the lava flows that are localised in the Catanda graben.

Carbonatitic pyroclastic rocks

Our study of the Catanda carbonatitic sequences reveals an overall abundance of pyroclastic rocks in comparison to lava flows. Therefore, eruptive processes involved in the emplacement of the Catanda carbonatites were dominated by explosive activity. In general, the Catanda pyroclastic rocks can be classified as lapilli tuffs, although some interbedded layers of tuff can also be found. These finer-grained layers might represent more explosive phases, more distal deposition or different transport processes. The carbonatitic pyroclastic rocks described here share similar features with those from other localities such as the Italian extrusive carbonatites of San Venanzo and Polino (Stoppa and Lupini 1993; Stoppa 1996; Stoppa and Schiazza 2013), as well as the Kaiserstuhl volcano, Germany (Keller 1989), where pyroclastic rocks and lava flows occur in close association.

Position of eruptive centres and type of volcanoes

Using geophysical methods, Silva and Pereira (1973) distinguished seven different eruptive centres in the Catanda area. However, it was not possible to describe volcanic structures such as dykes to verify the position of eruptive centres. In this study, considering the location and orientation of lava flows and pyroclastic rocks, seven specific locations can be considered as possible eruptive centres (shown in Fig. 3 with circled stars). Given the number of proposed eruptive centres, the shallow dips of pyroclastic horizons and the relatively thin sequences, we conclude that the Catanda carbonatitic area consisted of a number of small (monogenetic) volcanic edifices, as opposed to one dominant centre. These edifices were probably maars or tuff rings, similar to those described in other extrusive carbonatite localities such as Polino (Stoppa and Lupini 1993), Kaiserstuhl (Keller 1981, 1989) and Mt. Vulture (Stoppa and Principe 1998). This is supported by the typically low outward dips of strata; the thin pyroclastic sequences; the abundance of lithic fragments; and occasional low-angle cross-bedding attributed to deposition from pyroclastic surges, which are typical of maar tephra rings (White and Ross 2011 and references therein).

Origin of pelletal lapilli

Pelletal lapilli occur in several different pyroclastic deposits of the Catanda area. The cores of these lapilli are composed of quartz and microcline derived from the granite host rocks and less frequently accessory minerals derived from the carbonatite magma, including titaniferous magnetite and apatite. In other carbonatite localities where pelletal lapilli are described (Stoppa and Lavecchia 1992; Stoppa and Principe 1998), their cores are normally composed of minerals of a mantle origin and rock fragments that point to a significant depth for the formation of pelletal lapilli (Lloyd and Stoppa 2003). Here, the predominance of cores composed of shallow lithics indicates a near-surface depth for the formation of pelletal lapilli.

Spherical lapilli can form experimentally as a result of phreatomagmatic processes or by blowing compressed air through ultramafic magma (Zimanowski et al. 1997), so they do not represent a specific fragmentation mechanism. Gernon et al. (2012) attributed the formation of pelletal lapilli in kimberlites to a process known as “fluidised spray granulation”, which involves the coating of pyroclasts by a spray of melt droplets in diatremes. Unravelling the detailed processes of formation of pelletal lapilli and the relative importance of magmatic and phreatomagmatic fragmentation at Catanda requires further examination.

Lavas

Origin

The rocks we interpret as lavas are distinct from the observed pyroclastic lithofacies, and several features cannot easily be explained by welding or agglutination of pyroclastic deposits. The lavas exhibit very distinctive morphology and texture, forming coherent bodies with no discernible internal structure. In places, they contain abundant circular vesicles. Although they contain small quantities of granite clasts and disseminated crystal fragments (i.e. quartz, microcline, plagioclase), these are much more abundant in the pyroclastic lithofacies where they are organised into discrete layers. Layering of crystals and lithic clasts is expected to be preserved after welding (see Brown et al. 2008) but is not observed at Catanda. Further, welding is expected to produce sintered melt fragments and gradational contacts with volcaniclastic lithofacies (Brown et al. 2008), neither of which are observed at Catanda. Therefore, we argue that the lavas are not welded pyroclastic rocks but true lavas that erupted as liquids, flowed and subsequently became solid, such as those of the Kalyango flow in Fort Portal (Uganda) (Eby et al. 2009).

Mineralogy

Four different types of lavas can be distinguished based on mineralogical and textural features. The Utihohala, Ipunda and Jango lavas (Fig. 9b–d) contain more than 50 % carbonate, so they should be classified as carbonatite lavas (Bell 1989). On the other hand, the Huilala-Ungongué lavas contain only around 30 vol% carbonate, due to the presence of accessory minerals, especially silicate phenocrysts (augite and phlogopite) as well as cuspidine in the groundmass. Considering the abundance of these silicates, the Huilala-Ungongué flows are classified as silicocarbonatite lavas.

The Huilala-Ungongué flows are the most complex lavas according to mineral association, which is quite similar to that described in other localities such as Fort Portal (Von Knorring and Du Bois 1961; Nixon and Hornung 1973; Barker and Nixon 1989; Eby et al. 2009), where periclase is also noted in the base of the Kalyango flow. One significant difference at Catanda is the absence of melilite, which is described in a number of extrusive carbonatite localities (Hay 1978; Stoppa 1996).

The other Catanda lavas have a simple mineral association, with the exception of some variations including the occasional presence of alabandite in Utihohala flows, which is present in natrocarbonatitic lavas of the Oldoinyo Lengai volcano (Peterson 1990; Dawson et al. 1995).

Trachytoid textures

The well-developed trachytoid textures observed in lavas and juvenile lapilli from the Ipunda area were likely generated by accumulation of tabular calcite crystals in the magma reservoir. Similar textures were reported by Hayward and Jones (1991) in Middle Proterozoic extrusive calciocarbonatites from Qasiarsuk, South Greenland, as well as in the carbonatitic tephra from the Kerimasi volcano, Tanzania (Hay 1983; Zaitsev 2010); at both localities, tabular calcite crystals are interpreted as calcite pseudomorphs, which originated from primary natrocarbonatite minerals. Deans and Roberts (1984) described similar textures in pyroclastic rocks and lavas from the Tinderet foothills in Kenya, also proposing a pseudomorphic origin. However, Mariano and Roeder (1983) argue in favour of a primary magmatic origin for tabular calcite crystals. Dawson (1993), Zaitsev and Keller (2006) and Keller and Zaitsev (2006) studied “in situ” weathering and alteration processes of the Oldoinyo natrocarbonatites, where they describe polycrystalline calcite as a secondary product of the natrocarbonatitic mineral association. Nevertheless, the discussion about the origin of the trachytoid textures is still opened, and Zaitsev et al. (2013) proposed a natrocarbonatitic melt origin for the formation of carbonatite lavas at the Tinderet foothills.

Conclusions

Our conclusions are summarised as follows:

1. In the Catanda graben, a group of small monogenetic carbonatitic volcanic edifices are exposed; these consist mainly of pyroclastic rocks and minor lava flows.
2. The dominance of pyroclastic rocks indicates an important role for explosive volcanism in the area.
3. Pyroclastic rocks are mainly lapilli tuffs and minor tuffs occasionally comprising pelletal lapilli. Five different pyroclastic lithofacies have been distinguished in the area.
4. The cores to pelletal lapilli are mainly composed of shallow lithic grains indicating a near-surface depth of formation.
5. The eruptive products related to effusive pulses (lavas) are only located in the external parts of the graben, likely localised along major faults.
6. Based on mineralogical and textural features, four different types of lavas can be distinguished: Huilala-Ungongué (silicocarbonatites) as well Utihohala, Ipunda and Jango (carbonatites).
7. We have identified seven possible eruptive centres in the Catanda area. The volcanoes were likely tuff rings or maars.

Acknowledgments This research has been supported by project CGL2009-13758 of the Spanish Government and projects SGR-589 and SGR-444 of the Generalitat de Catalunya. Fieldwork in Catanda was also supported by the Hugh E. McKinstry fund, granted by the Society of Economic Geologists. Logistical assistance in the field was provided by the Departamento de Geologia da Universidade Agostinho Neto from Luanda, Angola. We acknowledge the collaboration and the hospitality of Felipe Correia and José Fortuna from Catanda village. We thank F. Stoppa, an anonymous reviewer and associate editor P.-S. Ross for their constructive comments.

References

Alberti A, Castorina F, Censi P, Comin-Chiaramoni P, Gomes CB (1999) Geochemical characteristics of Cretaceous carbonatites from Angola. J Afr Earth Sci 29:735–759

Bailey DK (1993) Carbonate magmas. J Geol Soc Lond 150:637–651

Barker DS, Nixon PH (1989) High-calcium, low-alkali carbonatite volcanism at Fort Portal, Uganda. Contrib Mineral Petrol 103:166–177

Bell K (1989) Carbonatites: genesis and evolution. Unwin Hyman Ltd, London, p 618

Brown RJ, Buse B, Sparks RSJ, Field M (2008) On the welding of pyroclasts from very low-viscosity magmas: examples from kimberlite volcanoes. J Geol 116:354–374

Dawson JB (1993) A supposed sövite from Oldoinyo Lengai, Tanzania: result of extreme alteration of alkali carbonatite lava. Mineral Mag 57:93–101

Dawson JB, Pinkerton H, Norton GE, Pyle DM, Browning P, Jackson D, Fallick AE (1995) Petrology and geochemistry of Oldoinyo Lengai lavas extruded in November 1988: magma source, ascent and crystallization. In: Bell K, Keller J (eds) Carbonatite volcanism. Oldoinyo Lengai and the petrogenesis of natrocarbonatite IAVCEI Proceedings in Volcanology 4 pp 47-69

De Boorder H (1982) Deep-reaching fracture zones in the crystalline basement surrounding the West Congo System and their control of mineralization in Angola and Gabon. Geoexploration 20:259–273

Deans T, Roberts B (1984) Carbonatite tuffs and lava clasts of the Tinderet foothills, western Kenya: a study of calcified natrocarbonatites. J Geol Soc Lond 141:563–580

Eby GN, Lloyd FE, Woolley AR (2009) Geochemistry and petrogenesis of the Fort Portal, Uganda, extrusive carbonatite. Lithos 113:785–800
Eley R, Grütter H, Louw A, Tunguno C, Twidale J (2008) Exploration geology of the Luxinga kimberlite cluster (Angola) with evidence supporting the presence of kimberlite lava. Extended Abstr. No. 9IKC-A-00166, 9th International Kimberlite Conference, Frankfurt
Gernon TM, Brown RJ, Tait MA, Hincks TK (2012) The origin of pelletal lapilli in explosive kimberlites eruptions. Nature Communications 3: article 832
Gomes CSF (1971) Ocorrência de cromita no carbonatito vulcânico da Catanda (Angola). Boletim dos Servicos de Geologia e Minas de Angola 20:55–59
Haggerty SE, Raber E, Naeser CW (1983) Fission track dating of kimberlitic zircons. Earth Planet Sci Lett 63:41–50
Hay RL (1978) Melilite-carbonatite tuffs in the Laetoli beds of Tanzania. Contrib Mineral Petrol 67:357–367
Hay RL (1983) Natrocarbonatite tephra of Kerimasi volcano, Tanzania. Geology 11:599–602
Hayward CL, Jones AP (1991) Cathodoluminescence petrography of middle proterozoic extrusive carbonatite from Qasiarsuk, South Greenland. Mineral Mag 55:591–603
Issa Filho A, Dos Santos ABRMD, Riffel BF, Lapido-Loureiro FEV, McReath I (1991) Aspects of the geology, petrology and chemistry of some Angolan carbonatites. J Geochem Explor 40:205–226
Jelsma H, Krishnan U, Perrit S, Preston R, Winter F, Lemotlo L, v/d Linde G, Armstrong R, Phillips D, Joy S, Costa J, Facatino M, Posser A, Kumar M, Wallace C, Chinn I, Henning A (2012) Kimberlites from Central Angola: a case study of exploration findings. 10th International Kimberlite Conference, Bangalore, Extended Abstr. No. 10IKC-42: 1-5
Keller J (1981) Carbonatitic volcanism in the Kaiserstuhl alkaline complex: evidence for highly fluid carbonatitic melts at the Earth's surface. J Volcanol Geotherm Res 9:423–431
Keller J (1989) Extrusive carbonatites and their significance. In: Bell K (ed) Carbonatites: genesis and evolution. Unwin Hyman, London, pp 70–88
Keller J, Zaitsev AN (2006) Calciocarbonatite dikes at Oldoinyo Lengai, Tanzania: the fate of natrocarbonatite. Can Mineral 44:857–876
Lapido-Loureiro FE (1968) Sub-volcanic carbonatite structures of Angola. Int Geol Congr (Prague), 23rd session, pp 147-161
Lapido-Loureiro FE (1973) Carbonatitos de Angola. Memórias e Trabalhos do Instituto de Investigação Científica de Angola 11:1–242
Lloyd EF, Stoppa F (2003) Pelletal lapilli in diatremes—some inspiration from the old masters. Geolines 15:65–71
Mariano AN, Roeder PL (1983) Kerimasi: a neglected carbonatite volcano. J Geol 91:449–455
Melgarejo JC, Costanzo A, Bambi ACJM, Gonçalves AO, Neto AB (2012) Subsolidus processes as a key factor on the distribution of Nb species in plutonic carbonatites: the Tchivira case, Angola. Lithos 152:187–201
Mitchell RH (1997) Kimberlites, organgeites, lamproites melilitites and minettes: a petrographic atlas. Almaz Press, Thunder Bay, Canada
Nixon PH, Hornung G (1973) The carbonatite lavas and tuffs near Fort Portal, Western Uganda. Overseas Geology and Mineral Resources, Institute of Geological Sciences, London 41: 168–179
Peres AM, Gomes CF (1969) Baddeleite da Catanda, Angola. Boletim dos Serviços de Geologia e Minas de Angola 18:27–34
Peres AM, Gomes CF, Cardoso-Simões MV (1968) As variedades semi-preciosas de olivina da Catanda-Angola. Boletim dos Serviços de Geologia e Minas de Angola 18:5–15
Peterson TD (1990) Petrology of natrocarbonatite. Contrib Mineral Petrol 105:143–155
Riley TR, Bailey DK, Lloyd FE (1996) Extrusive carbonatite from the Quaternary Rockeskyll Complex, West Eifel, Germany. Can Mineral 34:389–401
Robles-Cruz SE, Escayola M, Jackson S, Galí S, Pervov V, Watangua M, Gonçalves A, Melgarejo JC (2012) U-Pb SHRIMP geochronology of zircon from the Catoca kimberlite, Angola: implications for diamond exploration. Chem Geol 310–311:137–147
Silva MVS, Pereira E (1973) Estrutura Vulcânico-Carbonatitica da Catanda (Angola). Boletim dos Serviços de Geologia e Minas de Angola 24:5–14
Stoppa F (1996) The San Venanzo maar and tuff ring, Umbria, Italy: eruptive behaviour of a carbonate-melilitite volcano. Bull Volcanol 57:563–577
Stoppa F, Lavecchia G (1992) Late-Pleistocene ultra-alkaline magmatic activity in the Umbria-Latium region (Italy): an overview. J Volcanol Geotherm Res 52:277–293
Stoppa F, Lupini L (1993) Mineralogy and petrology of the Polino monticellite calciocarbonatite (Central Italy). Mineral Petrol 49: 213–231
Stoppa F, Principe C (1998) Eruption styles and petrology of a new carbonatitic suite from the Mt. Vulture (Southern Italy): the Monticchio Lakes Formation. J Volcanol Geotherm Res 80:137–153
Stoppa F, Schiazza M (2013) An overview of monogenetic carbonatitic magmatism from Uganda, Italy, China and Spain: volcanologic and geochemical features. J S Am Earth Sci 41:140–159
Sykes L (1978) Intraplate seismicity, reactivation of pre-existing zones of weakness, alkaline magmatism, and other tectonism postdating continental fragmentation. Rev Geophys 16:621–688
Torró L, Villanova C, Castillo M, Campeny M, Gonçalves AO, Melgarejo JC (2012) Niobium and rare earth minerals from the Virulundo carbonatite, Namibe, Angola. Mineral Mag 76:393–409
Von Knorring O, Du Bois CGB (1961) Carbonatitic lava from Fort Portal area in western Uganda. Nature 192:1064–1065
White JDL, Houghton BF (2006) Primary volcaniclastic rocks. Geology 34:677–680
White JDL, Ross P-S (2011) Maar-diatreme volcanoes: a review. J Volcanol Geotherm Res 201:1–29
Woolley AR (2001) Alkaline rocks and carbonatites of the world. Part 3: Africa, Geological Society of London, London
Woolley AR, Church AA (2005) Extrusive carbonatites: as brief review. Lithos 85:1–14
Zaitsev AN (2010) Nyerereite from calcite carbonatite at the Kerimasi Volcano, Northern Tanzania. Geol Ore Depos 52:630–640
Zaitsev AN, Keller J (2006) Mineralogical and chemical transformation of Oldoinyo Lengai natrocarbonatites, Tanzania. Lithos 91:191–207
Zaitsev AN, Wenzel T, Venneman T, Markl G (2013) Tinderet volcano, Kenya: an altered natrocarbonatite locality? Mineral Mag 77(3): 213–226
Zimanowski B, Büttner R, Lorenz V, Häfele H-G (1997) Fragmentation of basaltic melt in the course of explosive volcanism. J Geophys Res 102:803–814