Journal of African Earth Sciences 63 (2012) 12–31

Contents lists available at SciVerse ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

The Rungwe Volcanic Province, Tanzania – A volcanological review

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A R T I C L E I N F O

Article history:
Received 31 March 2011
Received in revised form 25 September 2011
Accepted 1 November 2011
Available online 16 November 2011

Keywords:
East African Rift System
Rungwe Volcanic Province
Explosive eruptions
Phonolite–trachyte
Volcano-tectonic interactions
Tanzania

A B S T R A C T

The Rungwe Volcanic Province in SW Tanzania is a densely populated area that is considered volcanically active. As part of the East African Rift System, a significant control of tectonic activity seems to exist on the location and also potential destabilization of volcanic edifices. Three large volcanoes, Ngozi, Rungwe, and Kyejo, dominate the landscape and all show contrasting eruptive behaviour in the recent geological past. Kyejo volcano is a flow-dominated volcano that had a historic lava flow eruption. Lake sediment cores, drilled in Lakes Malawi, Masoko, Rukwa, and Tanganyika, provide a record of frequent explosive eruptions in the last few tens of thousands of years. In combination with on-land stratigraphic observations, they constrain the minimum eruptive frequency of especially Rungwe and Ngozi volcanoes. Both volcanoes had Plinian-style eruptions in the Holocene. The most striking documented Rungwe eruption, the ca. 4 ka Rungwe Pumice, is a rare case of a Plinian eruption in near-wind-free conditions. Furthermore, the Rungwe Pumice, just like any other Rungwe tephra deposit, does not show any evidence of pyroclastic density current deposits. Apart from explosive eruptions at a range of scales happening every few hundred years at Rungwe, the volcano also experienced at least two sector collapse events generating debris avalanches. All existing evidence shows that the Rungwe Volcanic Province is prone to future significant explosive eruptions. To further assess, quantify and mitigate volcanic hazard risks, extensive and systematic multidisciplinary geological research, and both volcanic and tectonic monitoring are needed.

Contents

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1464-343X/$ - see front matter
doi:10.1016/j.jafrearsci.2011.11.005

1. Introduction

More than 1500 terrestrial volcanoes with known or suspected eruptions in the Holocene and considered prone to future eruptions are listed in the database of the Global Volcanism Program (GVP; Siebert et al., 2011). Most of the advances that were made in volcanology in the last 50 years are based on research that was focused on a limited number of volcanoes, often located in high-income countries (e.g. Italy, USA, Japan), leaving the majority of the world's volcanoes with potential future eruptions largely unstudied and unmonitored. This raises significant concerns within the scope of hazard and risk assessment and mitigation. Some of the most devastating historical eruptions occurred at volcanoes that were previously considered dormant or inactive, and/or were unmonitored, e.g. the 1982 eruption at El Chichón (Mexico; Tilling, 2009), the 1985 eruption of Nevado del Ruiz (Colombia; Mileti et al., 1991) or the 1991 eruption of Mt. Pinatubo (Philippines; Newhall et al., 1996).

Although natural hazards and disasters strike everywhere, in low- and middle-income countries, where the percentage of people living under the local poverty line is substantially higher than in high-income countries, populations are significantly more vulnerable to the impact of natural hazards when resulting economic losses are expressed in terms of proportion of Gross Domestic Product per capita (World Bank – United Nations, 2010). Lack of local expertise or hazard and risk awareness, a deficiency in financial resources and infrastructure, or limited means and experience with civil protection management, make it in many cases difficult for local authorities to cope with the impact of natural hazards, especially where local authorities are already overstretched with the struggle against income poverty so that geohazard risk can only be a low priority in the assignment of limited resources.

This paper presents a review of current knowledge on the volcanological history of the Rungwe Volcanic Province (RVP) in SW Tanzania which comprises three large volcanoes: Ngozi, Rungwe and Kyejo. A regional petrographical/volcanological reconnaissance study of the RVP was made in the 1950s by Harkin (1960), who noticed the occurrence of extensive pumice deposits which were attributed to explosive eruptions of Rungwe and Ngozi. Radiocarbon dating on palaeosols underneath tephra deposits found on land reveals that several explosive eruptions happened in the Holocene (Crossley, 1982; Fontijn et al., 2010a; Haynes et al., 1967, 1971). Holocene to Late Pleistocene RVP explosive eruptions are also partially recorded by volcanic ash beds in sediment cores from lakes in/around the RVP: Lake Masoko (Barker et al., 2000, 2003; Garcin et al., 2006; Gibert et al., 2002), Lake Malawi (Barker et al., 2007; Barry et al., 2002; Johnson et al., 2002, 2011; Williams et al., 1993), Lake Rukwa (Haberyan, 1987; Thevenon et al., 2002) and Lake Tanganyika (Huntsman-Mapila et al., 2009; Livingstone, 1965; Tiercelin et al., 1988a; Williamson et al., 1991). Recent effusive eruptions are interpreted from the occurrence of fresh-looking lava flow deposits on the flanks of Rungwe and Kyejo volcanoes (Harkin, 1960). A current expression of magma sources at depth, are the numerous CO_2 vents that are found all over the RVP. In some places CO_2 can accumulate to lethal concentrations, in others it is bottled for commercial use in fizzy drinks. All existing evidence points to a volcanically active region that is prone to future eruptions.

The administrative region of Mbeya in which the RVP is located, houses more than 2 million people (United Republic of Tanzania, 2002), the majority dependent on agriculture developed on the fertile RVP volcanic soils. The Rungwe district, with the majority of villages located within 20 km distance from the Rungwe volcano, houses ca. 300,000 people, largely unprepared for potential future volcanic eruptions.

2. Tectonic setting

The RVP, covering approximately 1500 km^2, is part of the East African Rift System (EARS). The RVP is located at the northern end of Lake Malawi (also called Lake Nyasa in Tanzania), where the EARS splits up into its Western and Eastern branches around the Tanzanian craton (Fig. 1). In SW Tanzania, the Western EARS branch is made up of the Tanganyika and Rukwa Rifts. The Southern Tanganyika and Rukwa Rifts form a straight NW-trending system with the Northern Malawi Rift, all together known as the South Tanganyika–Rukwa–North Malawi zone (Chorowicz et al., 1983; Delvaux, 2001). The Western EARS branch, well expressed in Ethiopia and Kenya, continues in central Tanzania as several branches (Fig. 1; Ebinger et al., 1997; Foster et al., 1997; Le Gall et al., 2004; Macheyeki et al., 2008). Between Dodoma and Mbeya, a poorly defined NE-trending rift segment occurs, partly expressed by the Usangu Basin. The RVP lies at the junction of the Usangu basin, the Rukwa Rift and the Northern Malawi Rift (Fig. 1).

Much of the research previously conducted in the RVP region, focussed on the tectonic setting and structure of the surrounding EARS basins, especially the Rukwa and Malawi Rifts, and on the timing relationship between rifting, lake sedimentation and volcanism (e.g. Branchu et al., 2005; Delvaux, 2001; Delvaux et al., 1992, 1998; Ebinger et al., 1987, 1989, 1993; Kervyn et al., 2006; Rosendahl et al., 1992; Specht and Rosendahl, 1989; Tiercelin et al., 1988b). Field and seismological data enabled a few researchers to gain insights into the tectonic setting of the RVP area, e.g. kinematic fault-slip analyses (Delvaux et al., 1992; Ring et al., 1992), data from temporary seismic stations (Delvaux and Hanon, 1993; Camelbeeck and Iranga, 1996) and focal mechanism solutions (waveform modelling of regional and teleseismic events by Brazier et al. (2005); regional stress inversions of centroïd moment tensors by Delvaux and Barth (2010)).

The RVP lies between three major border fault systems (Livingstone, Rukwa and Usangu border faults), all of which have been active in Miocene–Recent times. Some authors interpret the Rukwa–Malawi–Usangu Rifts as a triple junction that formed under a semi-radial extensional stress field (Delvaux et al., 1992, 2006; Delvaux and Hanon, 1993). Chorowicz (1989) interpreted the NW-striking faults between the Malawi and central Tanganyika rifts as an intra-continental transform fault zone. Ring et al. (1992) have used slip indicators in sedimentary strata in the Malawi basins to interpret a Pliocene rotation from ENE to SE-directed extension direction during the mid-Pliocene, during the same period as the volcano construction. Ebinger et al. (1989, 1993) suggest that the volcanism was concurrent with initial faulting, and that plate bending under the load of the volcanoes may have caused local deflections in the state-of-stress.

The current strike-slip faulting in the RVP, dominantly along (partly pre-existing) NW–SE to N–S faults, is an expression of a

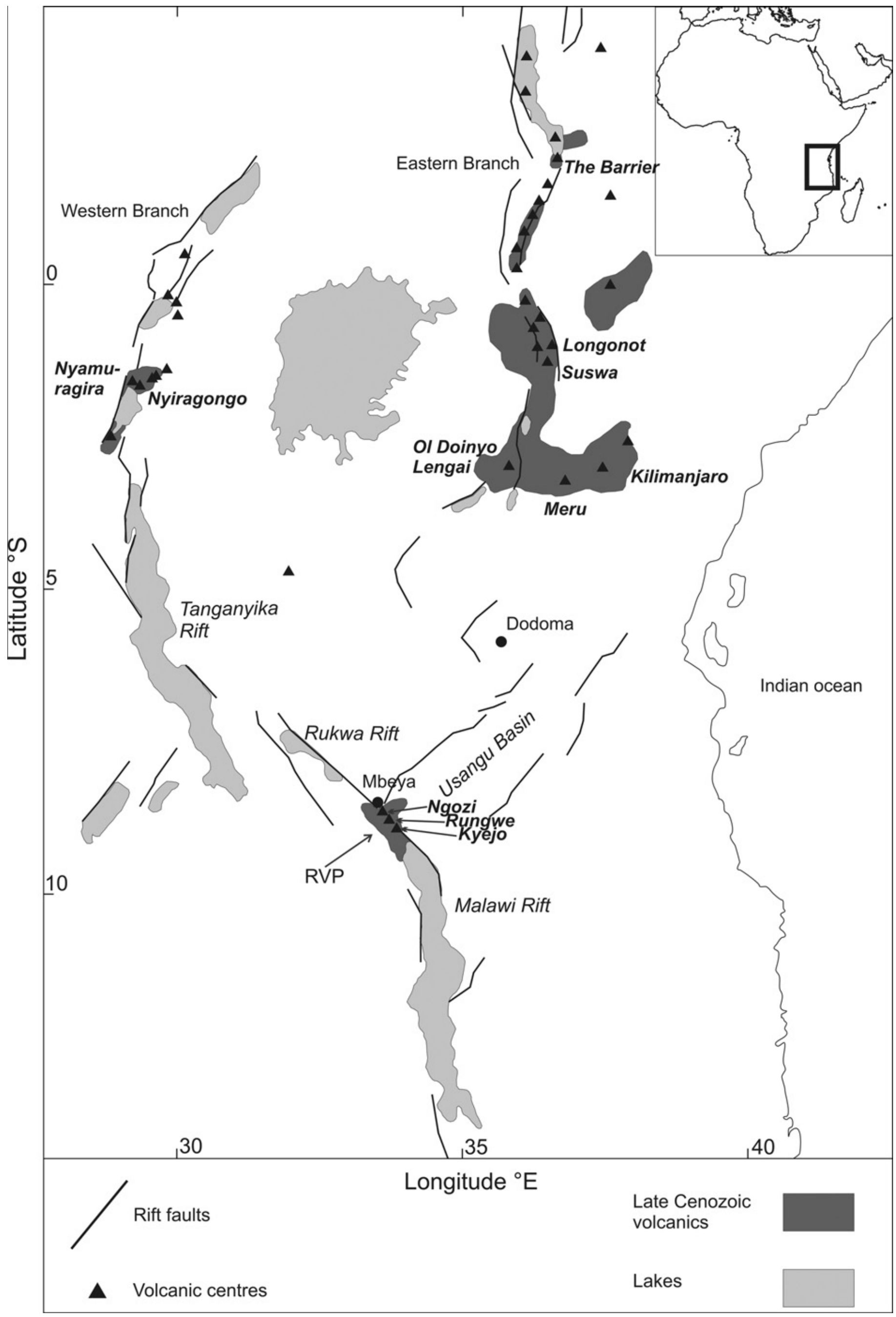

Fig. 1. Location of RVP within EARS showing surrounding rift basins: Malawi Rift, Tanganyika/Rukwa Rifts and Usangu Basin. Triangles indicate Holocene volcanic centres listed in the GVP database (Siebert et al., 2011). Names of a selection of the most important volcanoes are indicated. Three RVP volcanoes from NW to SE are: Ngozi, Rungwe, Kyejo. Rectangle in inset shows location within the African continent. Modified after Fontijn et al. (2010a).

compressional stress regime with the horizontal principal compression in ENE–WSW direction (Delvaux et al., 1992; Ring et al., 1992; Brazier et al., 2005; Delvaux and Barth, 2010). Focal mechanism solutions are consistent with a compressional regime and associated strike-slip faulting within the RVP, as well as the continuing normal faulting along major rift basin fault systems (Brazier et al., 2005; Delvaux and Barth, 2010).

Studies of the RVP volcano-tectonic architecture using field, remote sensing and K–Ar geochronology (Ebinger et al., 1989) and a Shuttle Radar Topography Mission Digital Elevation Model (USGS, 2006) combined with field data and geo-referenced air photos (Fontijn et al., 2010b), revealed a strong tectonic control on the location of volcanic centres. The observed tectonic lineaments are consistent with current tectonic models for the RVP. In the first place, the observations illustrate a strong control of tectonic activity over the location of the three main central volcanoes that are considered active, i.e. Ngozi, Rungwe and Kyejo (Fig. 2). Ngozi and Rungwe volcanoes are both located at the intersection of active faults characterizing the rift systems surrounding the RVP, especially faults associated with the Usangu Basin. A detailed spatial distribution analysis of all volcanic vents reveals a strong tectonic influence on vent spatial distribution. At Ngozi and Rungwe, a narrow NW–SE elongated zone of vents, the Ngozi–Rungwe Line, passes through the volcano summits and is consistent with the

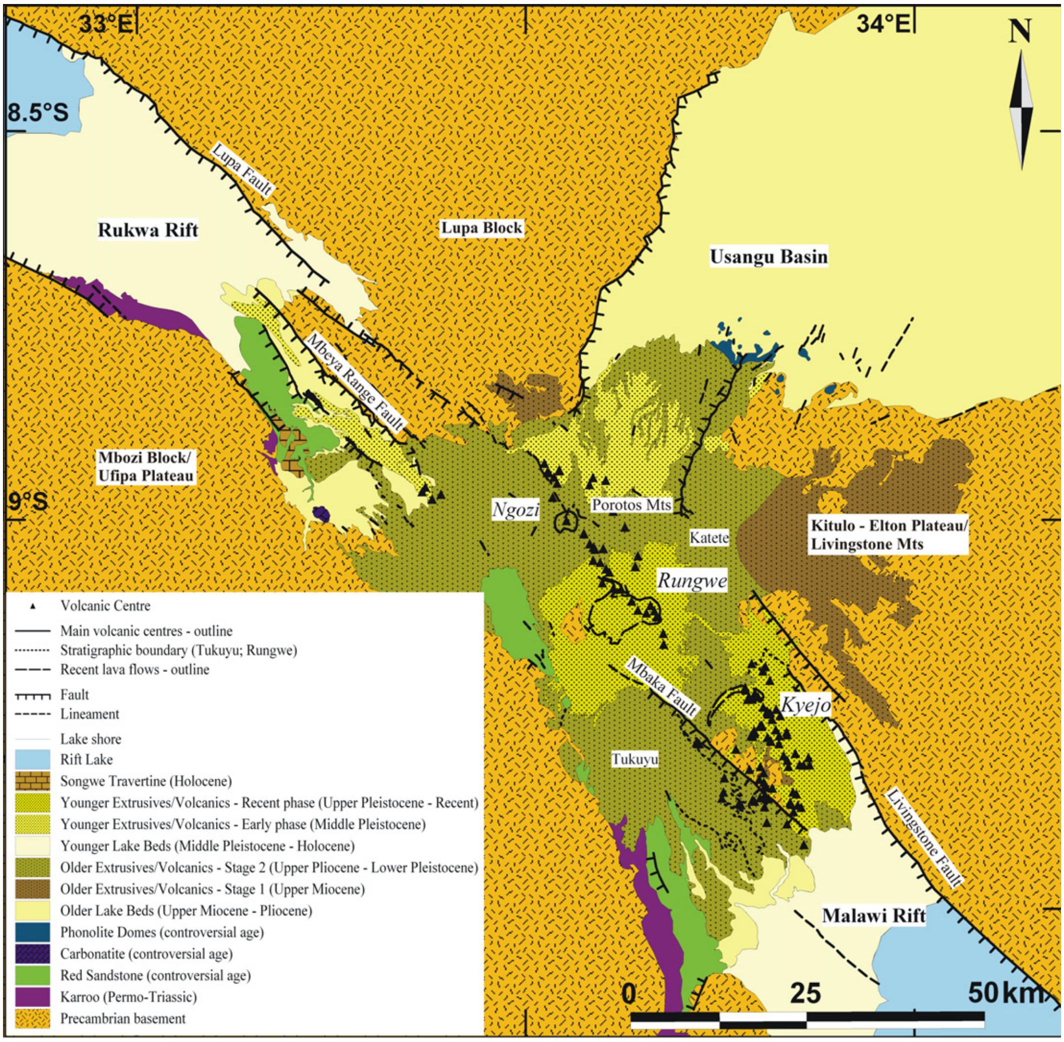

Fig. 2. RVP geological map, based on existing geological maps (Grantham et al., 1958; Harkin and Harpum, 1978; MacFarlane, 1963; Teale et al., 1962), volcano-tectonic maps of Delvaux et al. (1992) and Ebinger et al. (1989), and observations (lineaments) on remote sensing data. This map does not show deposits of Holocene explosive eruptions from Rungwe and Ngozi volcanoes, as they cover almost the entire RVP region (Fontijn et al., 2010a). The volcanic centres indicated in the NNE part of the region (Usangu Basin), form a phonolite dome field, and are not considered to belong to the Late Cenozoic stage of RVP volcanism. Modified after Fontijn et al. (2010b).

control of a major NW–SE buried rift fault intersecting with NNE–SSW faults. At Kyejo a separate cluster of vents occurs, generally also elongated NW–SE but with more scatter. In the South of the RVP, the Mbaka fault, oriented obliquely to the main vent alignment of Kyejo (Fig. 2), appears to play a secondary role on the location of several vents, including maars and tuff rings. The clear separation of the Ngozi–Rungwe Line from the Kyejo cluster suggests at least two different magmatic sources at depth (Fontijn et al., 2010b).

3. Volcanic stratigraphy

In addition to the three active volcanoes (Ngozi, Rungwe and Kyejo), more than 100 geomorphologically fresh cones and domes occur, most interpreted as belonging to the most recent phase of volcanism in the region (Section 3.2; Harkin, 1960; Fontijn et al., 2010b). A geological map of the area is presented in Fig. 2.

RVP alkaline volcanism started ca. 9 Ma ago and is dominated by effusive and explosive eruptions of basalt, trachyte and phonolite magmas. The volcanic activity has been divided into three stages based on field relationships (Harkin, 1960) and on approximately 50 published radiometric ages of volcanic rocks (K–Ar and $^{40}Ar/^{39}Ar$ dating, covering the entire RVP), mostly lava flow deposits (Ebinger et al., 1989, 1993; Ivanov et al., 1999): (1) Late Miocene: ~9.2–5.4 Ma, (2) Late Pliocene–Early Pleistocene: ~3–1.6 Ma, (3) Mid-Pleistocene–Recent: since ~0.6 Ma. The first two stages and third stage correspond to the *Older Extrusives* and *Younger Extrusives* respectively, as defined by Harkin (1960). Three WR K–Ar ages reported by Tiercelin et al. (1988b) and one laser fusion $^{40}Ar/^{39}Ar$ age on feldspar separates reported by Ivanov et al. (1999) are considered unrealistically high (e.g. Ebinger et al., 1993) and are not used further in this paper. Given the limited number of radiometric ages for such a vast area (>1500 km^2) and period of time (ca. 9 Ma), much more detailed and systematic field, dating and petrochemical work is needed to more closely constrain regional RVP stratigraphy, eruptive history and geohazard risks.

3.1. Early phases of volcanism – the Older Extrusives

An early phase of volcanism between 19 and 17 Ma ago (laser fusion $^{40}Ar/^{39}Ar$ dating on a matrix sample, whole rock (WR) K–Ar dating and Rb–Sr isochron age), i.e. well before the Late Cenozoic tectonic and volcanic activity since ca. 9 Ma ago, is suggested by Ivanov et al. (1999) and Rasskazov et al. (1999, 2003) to have occurred in the NNE part of the area (Usangu Basin, Fig. 2). This phase of volcanic activity has formed phonolitic domes and cones which still appear geomorphologically fresh today. Because of their fresh appearance, they were originally considered by Harkin (1960) to belong to the recent phase of RVP volcanism. In a study of the RVP volcano-tectonic architecture however, Fontijn et al. (2010b) suggested that the phonolitic domes and cones indeed show no spatial relationship with the recent RVP tectonic and volcanic features. Whereas a strong tectonic control exists on the location of recent volcanic vents (Section 2), no such relationship exists for the phonolitic domes and cones in the Usangu Basin. They were observed in the field to pre-date Late Cenozoic tectonic activity associated with the development of the Usangu Basin (Fontijn et al., 2010b).

The first stage of Late Cenozoic RVP volcanism is dated between ca. 9.2 and 5.4 Ma and is dominated by effusive eruptions of basaltic and phonolitic magmas as well as the emplacement of widespread phonolitic ignimbrites, e.g. the Songwe Tuffs found in lacustrine sections of N Lake Malawi (Fig. 3a). These Songwe Tuffs were dated by Ebinger et al. (1993) at 8.60 ± 0.04 Ma (single crystal laser fusion (SCLF) $^{40}Ar/^{39}Ar$ dating on anorthoclase separates) and grouped with welded tuff units dated at 8.16 ± 0.04 Ma (SCLF $^{40}Ar/^{39}Ar$ dating on K-feldspar separates). Crossley (1982) mentions the Songwe Tuffs as a series of pyroclastic flow deposits overlying deposits which are lithologically similar to the base of the shallow lacustrine Chiwondo Beds found in N Malawi and which span ages from >4 Ma to <1.6 Ma (e.g. Betzler and Ring, 1995; Sandrock et al., 2007). This correlation does however not seem straightforward as the Songwe Tuffs described by Crossley (1982) occur in an isolated outcrop. The Songwe Tuffs described by Ebinger et al. (1993) possibly do not correspond to those described by Crossley (1982) as the former did not overlie other non-volcanic sediments (C. Ebinger and U. Ring, personal communication, 2011). As yet, it is thus not clear how the Songwe Tuffs of either Ebinger et al. (1993) or Crossley (1982) correlate to one another and to the Chiwondo Beds. To constrain correlations of volcanic sediment sequences within the RVP and across the Malawi–Tanzania border as well as constrain the source and emplacement mechanisms, clearly more stratigraphic and chemical fingerprinting data of widespread units are needed.

Another example interpreted as a widespread sequence of phonolitic ignimbrites, the Elton phonolites, is found on the Elton Plateau (Fig. 2) and is interbedded with basalt lava flows (Elton basalts, Fig. 3a). An Elton basalt sample dated by Ebinger et al. (1993) yields a WR K–Ar age of 7.43 ± 0.19 Ma. The youngest dated sequence of this stage, the Masukulu Phonolites, occurs E of the Mbaka Fault, is interpreted as containing basaltic and phonolitic lavas and phonolitic ignimbrites, and dated at 5.52 ± 0.03 Ma (single crystal laser fusion $^{40}Ar/^{39}Ar$ dating on K-feldspar separates; Ebinger et al., 1993).

It is not clear whether the "phonolitic ignimbrites" of the Songwe Tuffs and the Elton Plateau referred to by Ebinger et al. (1993) were effectively emplaced by pyroclastic density currents (PDCs) or only indicate the presence of widespread tephra deposits that could result from primary PDCs or pyroclastic fallout, or from secondary mudflow deposits. The Songwe Tuffs of Crossley (1982) are described as "a series of pyroclastic flows with occasional beds of water deposited fine ashy clays and rolled volcanic clasts". This description reminds more of reworked pyroclastic material emplaced by mudflows than by PDCs (pyroclastic flows; e.g. Vallance, 2000). Harkin (1960) describes tuffs, corresponding to phonolitic ignimbrites of Ebinger et al. (1993), as containing various amounts of pumice lapilli and lithics, and sometimes almost entirely made up of ash. Such grain size characteristics are typical for deposits emplaced by a flow mechanism, either pyroclastic density currents or mudflows. Detailed volcano stratigraphic work with grain size distribution and deposit componentry data for earlier studied sections could help lift the ambiguity.

Harkin (1960) considered the now largely eroded Katete volcano (Fig. 2) NE of Rungwe as a possible source of large explosive eruptions during this first period of volcanic activity. Katete, which has never been studied systematically, is so far interpreted as a volcano very similar to present-day Rungwe. WR K–Ar dating of a phonolite/trachyte sample from Katete volcano (2.35 ± 0.04 Ma; Fig. 3a; Ebinger et al., 1989) suggests that the Katete volcano was active during the Late Pliocene and thus at least partly belongs to the second stage of volcanism.

In the second stage (ca. 3–1.6 Ma; Fig. 3a) the same type of volcanism is established as in the first stage: both basalt lava flows and phonolitic ignimbrites are erupted, with perhaps a tendency towards effusive-dominated activity. Next to basaltic lava flows, many trachytic and phonolitic lavas are also interpreted to have been emplaced from several eruptive centres spread around the RVP. These volcanic rocks are referred to by Harkin (1960) as the Older Basalts and Older Trachytes, and are thought to make up much of the Porotos Mountains, in which the Ngozi caldera is located (Fig. 2). Harkin (1960) considered the Ngozi volcano to belong to the *Older Extrusives* stage, but suggested that the caldera-forming eruption of Ngozi was Late Quaternary or even Holocene in age. A more narrowly defined Holocene age of the Ngozi caldera-forming eruption is now proposed based on new and more detailed field investigations (Fontijn et al., 2010a; Section 3.2). Ebinger et al. (1989) dated a trachyte lava sample from the Porotos Mountains E of Ngozi caldera, at 2.2 ± 0.2 Ma (WR K–Ar dating, Fig. 3a), suggesting a Late Pliocene age for at least a part of the mountain ridge and the Ngozi edifice.

Another major eruptive centre interpreted to be from the second stage of RVP volcanism is the Tukuyu shield, currently thought to be almost entirely made up of basaltic lavas, although it has never been systematically investigated as yet either. Today, the town of Tukuyu is built on top of the shield volcano. The Tukuyu volcano was originally considered by Harkin (1960) as part of the *Younger Extrusives*, but WR K–Ar dating by Ebinger et al. (1989, 1993) and SCLF $^{40}Ar/^{39}Ar$ dating by Ivanov et al. (1999) provide ages for three Tukuyu (basalt) lavas between 1.34 ± 0.02 Ma and 2.12 ± 0.04 Ma, suggesting that the Tukuyu shield belongs to the second stage of volcanism (Fig. 3a).

3.2. Late Quaternary volcanism – the Younger Extrusives

Since ca. 0.6 Ma ago a new phase of volcanic activity was established in the RVP. The oldest volcanic rocks from this stage are found in the N and NW of the region, towards the Usangu and Rukwa Rifts respectively (Fig. 2). The basal lava flow deposits in the Songwe basin (towards the Rukwa Rift) are made up of trachytes and were dated at 0.55 ± 0.01 Ma (K–Ar dating on anorthoclase separates; Fig. 3b; Ebinger et al., 1989). Boulders of these trachytes also occur within immediately overlying deposits interpreted as ignimbrites. The youngest lava flow units in the Songwe basin are olivine basalts and melanephelinites. The basal lava flow deposits in the SW Usangu basin are formed by olivine basalts dated at 0.57 ± 0.01 Ma (WR K–Ar dating; Ebinger et al., 1989). The youngest, undated, lava flow units documented so far in the Usangu Basin are trachyandesites originating from cones located 4–8 km NNW of Ngozi volcano. Both in the Songwe and Usangu Basins, the youngest lava flow units are covered with a tephra blanket from recent eruptions from Rungwe and Ngozi (Ebinger et al., 1989; Fontijn et al., 2010a).

In addition to some of the dated flows in the Songwe and Usangu basins, Harkin (1960) interprets other isolated eruptive centres, e.g. Tangano and Ntumbi in the Porotos Mountains, which

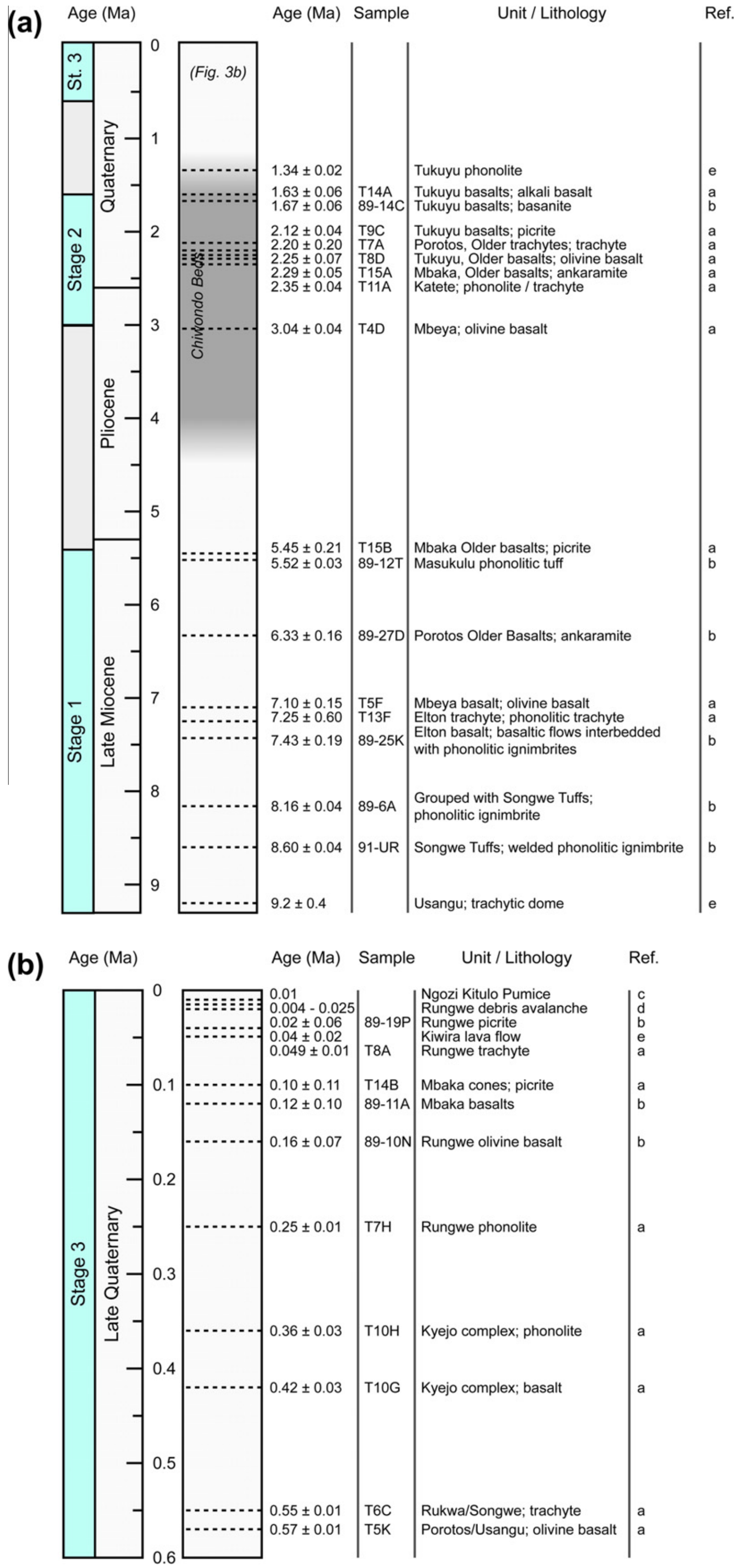

Fig. 3. Compilation of radiometric ages for the three stages of RVP volcanic activity. (a) Stage 1 and 2 (Late Miocene–Pliocene), (b) Stage 3 (Late Pleistocene – Recent). References: a: Ebinger et al. (1989); b: Ebinger et al. (1993); c: Fontijn et al. (2010a); d: Fontijn et al., unpublished data; e: Ivanov et al. (1999). Ages from a, b and e are K–Ar or $^{39}Ar/^{38}Ar$ ages; those from c and d are from radiocarbon dating. Sample numbers, when given, refer to sample numbers mentioned in original publications. Age data from tephra beds found in lake sediment cores are presented in Fig. 4. A more detailed stratigraphy for the Holocene is presented in Fig. 7.

may also belong to this earlier phase of the third stage of volcanism.

The most recent RVP volcanism, thought to correspond roughly to Upper Pleistocene to Holocene activity, is concentrated at the three large active central volcanoes Ngozi, Rungwe and Kyejo. Fig. 2 illustrates geomorphologically fresh eruptive centres as recognized in the study of the volcano-tectonic architecture of the region (Fontijn et al., 2010b).

3.2.1. Sediment cores

A key record for the recent RVP eruptive history, are sediment cores from lakes in/around the RVP. These sediment cores reveal numerous tephra horizons for which the ages can be interpolated from ^{14}C dating on the organic matter-rich sediment in the cores, from varve counting or, in case of the uppermost sediments, from down-core extrapolation of ^{210}Pb analysis (Fig. 4). The most important record so far is that from Lake Masoko, ca. 25 km SSE of

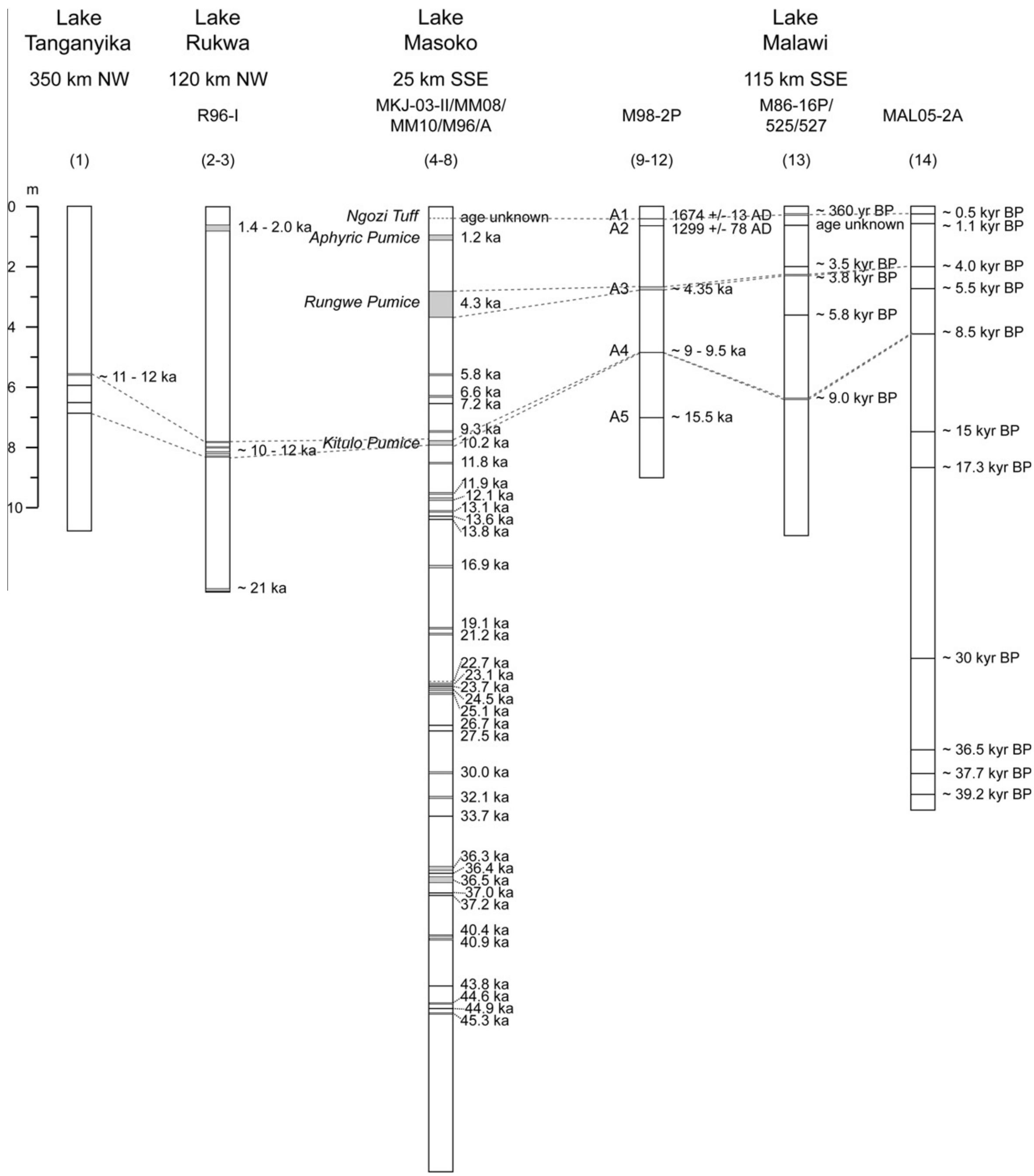

Fig. 4. Schematic overview of tephra beds reported in sediment cores drilled in Lakes Tanganyika, Rukwa, Masoko and Malawi. Distance and direction of core locations are given relative to Rungwe volcano. Correlations between cores are tentative based on age constraints, and should be confirmed with geochemical data. Ages reported in ka are interpolated from calibrated radiocarbon dates, i.e. are in fact ka cal BP. The youngest ash bed in section M86-16P/525/527 is dated by down-core extrapolation of ^{210}Pb analysis of the topmost sediments. Ages indicated in AD are dated by varve counting. All logs are drawn to scale, except for MAL05-2A, which is drawn on a time scale as the presence of tephra was only derived from the occurrence of K:Ti peaks and no depths and or thicknesses for ash beds were reported. Ash layers less than 1 mm are not shown in the Masoko record, except for the uppermost cryptotephra horizon. References are given above each log. 1: Livingstone (1965); 2: Barker et al. (2002); 3: Thevenon et al. (2002); 4: Barker et al. (2000); 5: Barker et al. (2003); 6: Garcin et al. (2006); 7: Garcin et al. (2007); 8: Gibert et al. (2002); 9: Barker et al. (2007); 10: Barry et al. (2002); 11: Filippi and Talbot (2005); 12: Johnson et al. (2002); 13: Williams et al. (1993); 14: Johnson et al. (2011).

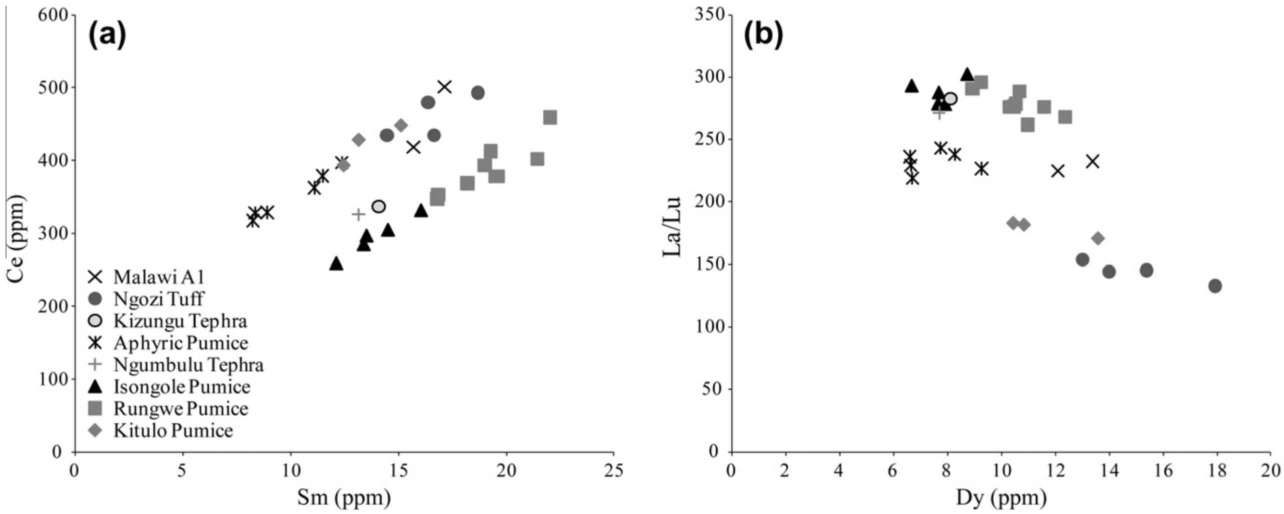

Fig. 5. Variation diagrams of selected incompatible trace elements and element ratios illustrating a possible affinity of the most recent ash layer found in Lake Malawi cores (i.e. A1 described and dated by Barry et al. (2002) at 1674 ± 13 AD; chemical data from Williams et al. (1993)) with Ngozi Tuff, an ignimbrite deposit from Ngozi caldera (Fontijn et al., 2010a). A correlation with Aphyric Pumice, a fall deposit from Rungwe volcano (Fontijn et al., 2010a), can however not be ruled out. (a) Ce vs. Sm; (b) La/Lu vs. Dy. Legend shown in (a) also applies to (b). Deposits shown in stratigraphic order, Malawi A1 and Ngozi Tuff being the youngest. Ngozi Tuff and Kitulo Pumice are deposits from Ngozi, other deposits from Rungwe (Fontijn et al., 2010a).

Rungwe volcano, where 70 tephra layers are found in cores MM08, MM10, M96-A, M96-B, M96-C and MKJ-03-II, spanning the last ∼45 ka (Barker et al., 2003; Garcin et al., 2006; Gibert et al., 2002; Williamson et al., 1999). Tephra layer thickness varies from less than 1 mm to almost 1 m. Light coloured, fine ash to small lapilli of phonolitic to trachytic composition are dominant, although some dark coloured beds enriched in ilmenite and titanomagnetite also occur (Garcin et al., 2006; Williamson et al., 2008). The latter tend to occur mostly in the Late Pleistocene part of the record, and presumably originate from Kyejo, from one of its satellite vents or from the late Pleistocene phreatomagmatic explosions events which resulted in basaltic maars along the Mbaka fault system. As far as is known, Kyejo and its satellite vents have only known eruptions of mafic magmas (Harkin, 1960), producing dark-coloured ash beds. The light-coloured tephra beds are interpreted to originate from Rungwe or Ngozi, whose ubiquitous pumice and ash deposits are similarly light-coloured, consistent with their evolved trachytic/phonolitic composition (Fontijn et al., 2010a). Fig. 4 presents key tephra layers observed in the compiled Masoko record (Garcin et al., 2006) and other lake records from the region. The most prominent tephra beds occur at interpolated ages of 36.5 ka (21.9 cm thick beige coarse ash observed in core M96-B), 36.3 ka (14.1 cm of beige fine to medium-sized ash observed in core M96-A), 16.9 ka (11.2 cm of grey fine ash observed in core M96-A), 12.1 ka (11 cm of beige-brown medium to coarse ash observed in core M96-A), 10.2 ka (15 cm of light grey to beige coarse ash to small lapilli observed in core M96-B, correlated with Kitulo Pumice; Section 3.2.2, Fontijn et al., 2010a), 4.3 ka (76–100 cm of light grey coarse ash to small lapilli observed in core M96-B, correlated with Rungwe Pumice; Section 3.2.4, Fontijn et al., 2010a), and 1.2 ka (17.5 cm of beige-grey laminated fine, medium to coarse ash observed in core MM10; the lower 3.5 cm have been chemically correlated to Aphyric Pumice; Section 3.2.4, Fontijn et al., 2010a).

Several sediment cores drilled in the northern basin of Lake Malawi, at an average distance of 115 km SSE to Rungwe, also show frequent silicic ash layers in the last few tens of thousands years (Fig. 4; Barker et al., 2007; Barry et al., 2002; Filippi and Talbot, 2005; Johnson et al., 2002, 2011; Williams et al., 1993). Cores drilled in the central Lake Malawi basin do not contain tephra horizons (Johnson et al., 2011). Two ash layers are described within the last 500 years in northern Lake Malawi by Williams et al. (1993) and Barry et al. (2002). The most recent one is dated at ca. 360 yr BP based on down-core extrapolation of ^{210}Pb analysis of the topmost sediments and an average recent sedimentation rate of 1.2 mm/yr (Williams et al., 1993). This age is consistent with that obtained by varve counting for the most recent tephra layer described in other northern Lake Malawi cores by Barry et al. (2002), i.e. layer A1 with an inferred age of AD 1674 ± 13. This latter bed is correlated to a cryptotephra horizon in Lake Masoko core MKJ-03-II identified by peaks in Na_2O and K_2O concentrations and visible sanidine crystals (Garcin et al., 2007). Incompatible trace element analyses of the most recent Lake Malawi ash layer reported by Williams et al. (1993) show an affinity with the most recent on-land deposit recorded by Fontijn et al. (2010a), i.e. the Ngozi Tuff (Fig. 5; Section 3.2.2). A correlation with the Aphyric Pumice (Fig. 5; Section 3.2.2) cannot be ruled out; more detailed/systematic chemical data are needed to constrain the correlation.

The second most recent ash bed in Lake Malawi is dated by varve counting at AD 1299 ± 78 (A2 of Barry et al., 2002) corresponding to the ca. 1 ka cal BP layer of Barker et al. (2007) and possibly also to the 1.2 ka cal BP layer found in Masoko cores MM8 and MM10 (Barker et al., 2000; Garcin et al., 2006), which has at least partly been chemically correlated to the Aphyric Pumice (Fig. 4; Section 3.2.4; Fontijn et al., 2010a).

The most prominent tephra bed reported in almost all northern Lake Malawi cores contains pumice lapilli and occurs at interpolated ages 3.8–4.4 ka cal BP (Barker et al., 2007; A3 of Barry et al., 2002; Johnson et al., 2002; Williams et al., 1993) and is interpreted to correspond to the Rungwe Pumice (Section 3.2.4). The reported thickness varies from a few mm to 30 cm, although this latter thickness is probably due to syn-sedimentary slumping. The primary depositional thickness in northern Lake Malawi for the Rungwe Pumice has been physically modelled by Fontijn et al. (2011) to be 3 ± 2 cm. Another pumice-bearing ash horizon with interpolated radiocarbon ages at ca. 8.5–9.5 ka cal BP has been reported in some cores (Fig. 4; Barker et al., 2007; A4 of Barry et al., 2002; Filippi and Talbot, 2005; Johnson et al., 2002, 2011; Williams et al., 1993) and is ascribed to the Kitulo Pumice (Section 3.2.4), although chemical data are needed to constrain this correlation.

In Lake Rukwa sediment cores, weathered tephra is common throughout the stratigraphy, but more discrete ash horizons have been described at interpolated ages of ca. 1.4–2 ka cal BP, 9–12 ka cal BP and 21 ka cal BP. The ca. 4 ka Rungwe Pumice is not preserved in the Rukwa cores, where ash layers do not occur as pure tephra beds, but rather as mixed sand and ash debris (Thevenon et al., 2002). Mid- and Late Holocene deposition hiatuses and bottom sediment mixing associated with dry conditions and low lake stands might have prevented the recovery of the Rungwe Pumice ash (Barker et al., 2002; Talbot and Livingstone, 1989; Thevenon et al., 2002). The horizons around the Pleistocene–Holocene boundary occur as up to four distinct layers (Barker et al., 2002; Haberyan, 1987; Talbot and Livingstone, 1989; Thevenon et al., 2002), and have also been found in cores drilled in southern Lake Tanganyika, ca. 300 km NW of Rungwe volcano (Fig. 4; Livingstone, 1965). The timing and correlation of the different ash layers suggest a peak in regional volcanic activity ca. 13–10 ka cal BP, i.e. at the Pleistocene–Holocene boundary (Delvaux and Williamson, 2008).

3.2.2. Ngozi

Ngozi (volcano 0202-164 in the GVP database: Siebert et al., 2011; alternative spelling: Ngosi) is part of the E–W trending Porotos Mountain ridge (Fig. 2) thought to be largely made up of basalt, phonolite and trachyte lava flow deposits erupted from numerous centres (Harkin, 1960) that were probably already active during Stage 2 of RVP volcanism (Section 3.1). Ngozi is not readily distinguished in the topography except for its irregular-shaped summit caldera (Fig. 6). The collapse caldera measures ca. 3 km across. The caldera rim rises on average ca. 300 m above the surrounding topography, and has an elevation of ca. 2300 to maximum 2620 m above sea level (asl). Only the S half of the caldera is occupied by a lake; in the N half a forested plateau rises 100–150 m above the lake. The S edge of the caldera displays a notch in the rim. The irregular shape of the caldera is consistent with the idea that it formed relatively recently and that it is still quite an unstable structure. Recent earthquake activity in December 2009 in the N Malawi Rift (Biggs et al., 2010) has possibly triggered small landslides along the steep inner caldera slopes that have exposed new sections. Reconstructing the stratigraphic record of Holocene explosive eruptions, Fontijn et al. (2010a) identified two deposits of large explosive eruptions from Ngozi: the ca. 10–12 ka Kitulo Pumice and the <1 ka Ngozi Tuff (Fig. 7).

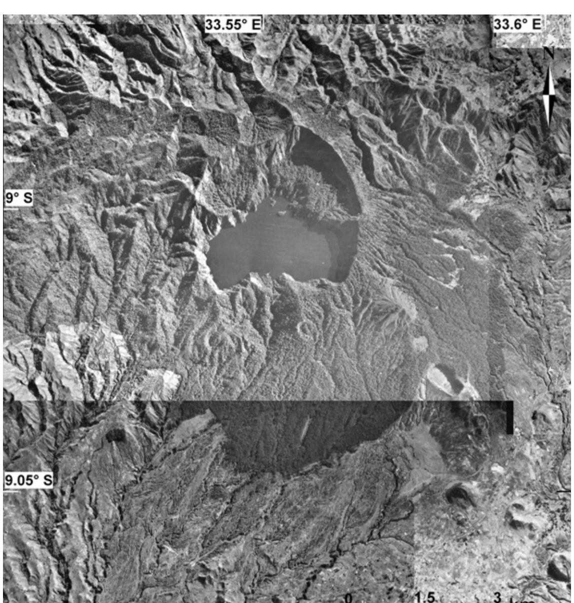

Fig. 6. Air photo view of Ngozi caldera illustrating its irregular shape. The base of the volcano is not clearly distinguishable from its surrounding topography.

The Kitulo Pumice is a trachytic (Fig. 8), cream-coloured, aphyric to very poorly sanidine-phyric pumice lapilli breccia deposit, mostly found on the Kitulo Plateau (Fig. 2), which was chemically correlated to an ash bed dated at 10.2 ka cal BP in Lake Masoko sediment core M96/A (Fig. 4; Barker et al., 2000, 2003; Fontijn et al., 2010a; Garcin et al., 2006; Gibert et al., 2002). In all rift lakes surrounding the RVP, i.e. Lakes Malawi, Rukwa and Tanganyika, ash beds dated around 10–12 ka have been found as well (Fig. 4; Barker et al., 2007; Barry et al., 2002; Livingstone, 1965; Thevenon et al., 2002; Williams et al., 1993). Carbonized wood/charcoal samples found in pumiceous tuff deposits close to the NW shore of Lake Malawi (Ngana Tuff; Crossley, 1982) were radiocarbon dated at 11,000 ± 300 yr BP (Haynes et al., 1967) and 10,170 ± 140 yr BP (Haynes et al., 1971), respectively. These lake and on-land ash beds have been tentatively correlated to the Kitulo Pumice, based on age constraints (Fontijn et al., 2010a). Correlations should however be confirmed with geochemical data. It is moreover not clear from descriptions by Clark et al. (1970) and Haynes et al. (1967, 1971) whether the dated on-land pumiceous tuffs represent fall, flow, or secondary reworked pumice and ash deposits.

Although the dispersal pattern of the deposit is not well constrained, the sections where the deposit is preserved, suggest an eruption at least on the scale of the entire RVP with a minimum deposit volume of 2–3 km^3. The Kitulo Pumice classifies at least as a Volcanic Explosivity Index (VEI; Newhall and Self, 1982) 5? (i.e. the VEI cannot be accurately estimated due to a limited dataset) event. Due to its large scale, the Kitulo Pumice was interpreted to have been emplaced during the caldera-forming eruption of Ngozi (Fontijn et al., 2010a).

Based on field reconnaissance, the S and SE Ngozi caldera walls are suspected to be largely made up of unconsolidated tuff deposits from the Ngozi Tuff eruption, an ignimbrite-forming eruption dated at <1 ka (Fig. 7). The Ngozi Tuff is an often multiple meters thick, light grey, matrix-supported valley-filling tuff deposit with clasts of white subrounded aphyric to very phenocryst-poor pumice lapilli and grey porphyritic pieces of lava. Pumice clasts are of trachytic composition (Fig. 8). The deposit has up to now mostly been found S of the caldera, and also occurs as a cm-scale veneer of white ash in several locations up to 10 km SSE of the volcano. Harkin (1960) mentions the occurrence of a nearly aphyric, whitish, relatively lithic-rich pumice deposit around Ngozi of increasing thickness and lapilli size towards Ngozi volcano. It is unclear whether this could be a fall deposit associated to the Ngozi Tuff eruption. More fieldwork, especially W and N of the volcano, is needed to closely constrain the distribution pattern of this recent deposit. It was proposed by Fontijn et al. (2010a) that the Ngozi Tuff eruption reshaped the Ngozi caldera to its near-present form after it had been formed by the Kitulo Pumice eruption.

3.2.3. Rungwe – sector collapse

Rungwe (volcano 0202-166 in the GVP database: Siebert et al., 2011) is the largest and highest volcano in the RVP, and is located centrally in the region (Fig. 2). It is interpreted as a stratovolcano with a ca. 15 km basal diameter and relatively gentle slopes (ca. 15°), rising to a maximum elevation of 2956 m asl, or ca. 1500 m above the surrounding landscape. The volcano has a ca. 4×5 km^2 amphitheatre-shaped summit depression open to the WSW that is marked by a prominent scar up to 300 m high on its N and E side (Fig. 9). The Rungwe summit depression was originally interpreted by Harkin (1960) as a collapse caldera, but field mapping by Fontijn et al. (2010a, 2010b) strongly suggests that the caldera, as first suggested based on a remote sensing survey by De Craene (2005), resulted from a sector/flank collapse generating a debris avalanche, i.e. is interpreted here as a so-called avalanche caldera (Siebert, 1984). A mound-field consisting of small hills up to 7 m high, constructed by lava debris, was

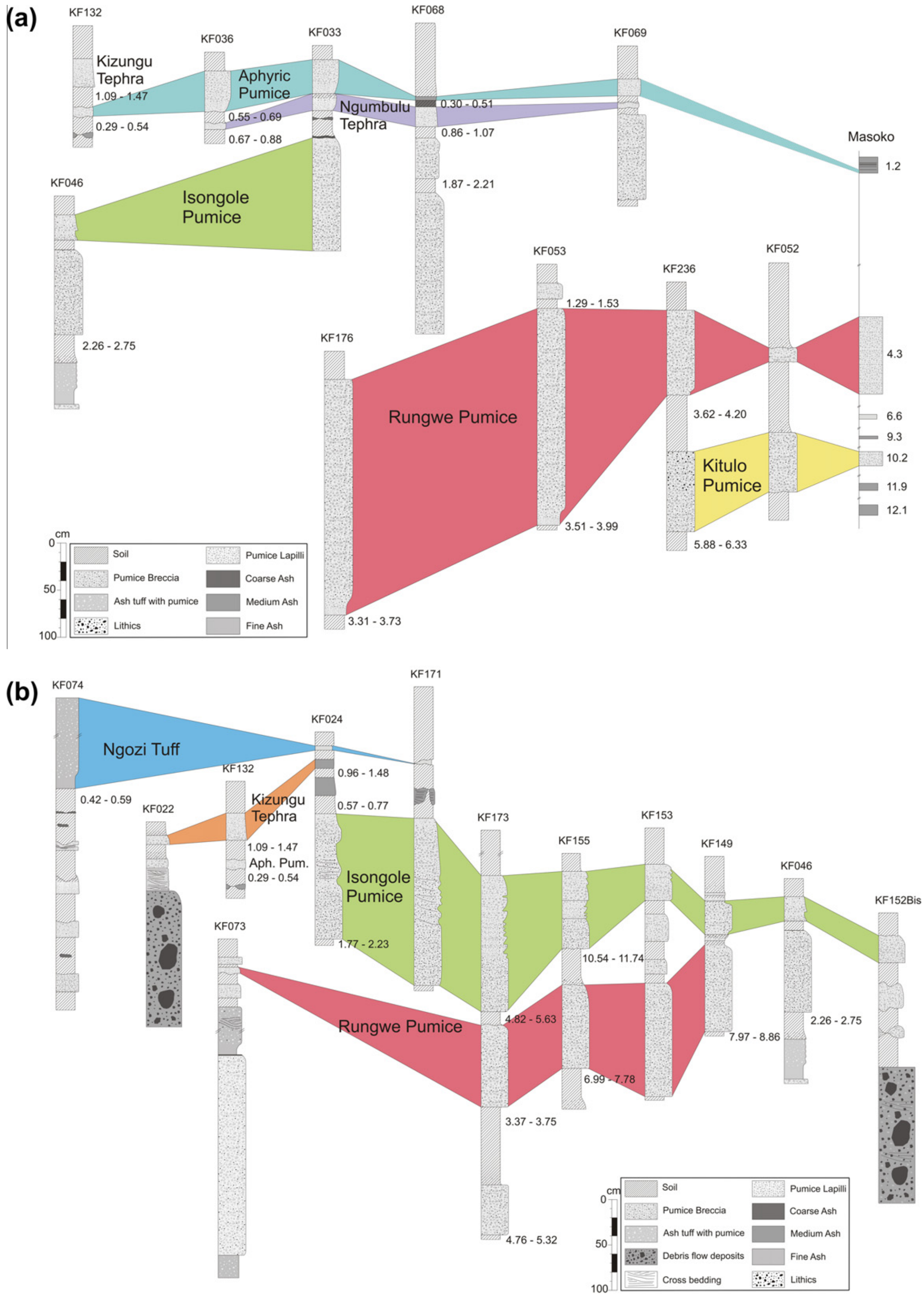

Fig. 7. Stratigraphic correlations between representative outcrops surrounding Rungwe and Ngozi volcanoes. Palaeosol ages indicated in ka cal BP at 2σ confidence level. Correlations are made on the basis of field evidence supported with chemical fingerprinting (Fontijn et al., 2010a). As a reference, logs of sections KF046 and KF132 are shown in both (a and b). (a) Sections mostly located W of Rungwe and E of Ngozi volcanoes. Ngozi Tuff is a deposit from Ngozi volcano; other regionally correlated deposits originate from Rungwe volcano. Debris flow deposits shown in log KF022 are possibly associated to the Rungwe sector collapse generating a debris avalanche (Section 3.2.3), those in KF152Bis are not associated to this debris avalanche. Aph. Pum.: Aphyric Pumice. (b) Sections mostly located E of Rungwe volcano. Kitulo Pumice is a deposit from Ngozi volcano; other regionally correlated deposits originate from Rungwe volcano. Modified after Fontijn et al. (2010a).

described by Harkin (1960) and is located ca. 16 km SW of the Rungwe summit depression (Fig. 9). Harkin (1960) interpreted the origin of the mound-field as a lahar deposit, but from a classic study by Siebert (1984), it has been documented that hummocky

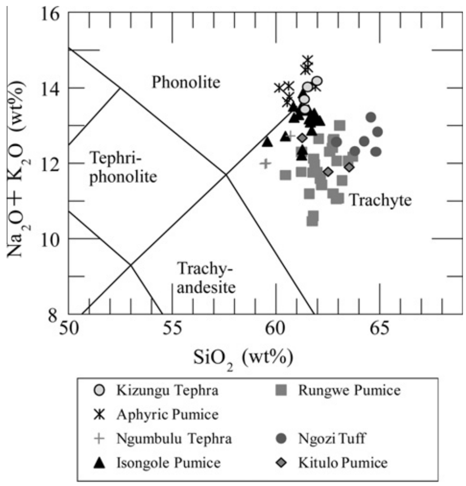

Fig. 8. Total Alkali–Silica (TAS) diagram after Le Bas et al. (1986) for deposits from Holocene explosive eruptions at Ngozi and Rungwe. Chemical data presented by Fontijn (2011) and Fontijn et al. (2010a).

topography, together with an amphitheatre-shaped scar at the volcano's summit, is characteristic for debris avalanche deposits (DADs; Ui et al., 2000). This field of small hummocks described by Harkin (1960) corresponds to the distal regions of the DAD (e.g. Clavero et al., 2002; Dufresne and Davies, 2009; Siebert, 1984).

During field work conducted by K.F. and G.G.J.E. in July 2008, the spatial extent of the hummocky terrain associated with the DAD was mapped wherever possible in both the distal and more proximal areas where the DAD was expected, i.e. SW of Rungwe (Figs. 9 and 10). The mound-field described by Harkin (1960) is made up of conical hills ranging in height between ca. 3 m and 7–8 m. The hill shape is usually nearly perfectly conical with a base diameter approximately twice the height (Fig. 10d and e). The hummocks are made up of very poorly sorted lava debris blocks with grain sizes ranging from mm-scale (matrix) to several meters (blocks). Some blocks show features which remind of small-scale jigsaw cracks, i.e. the blocks are broken but their internal structure remained intact (Fig. 10f; Ui et al., 2000). Unfortunately no large outcrops have been found where large-scale internal structures, e.g. jigsaw cracks in massive blocks on outcrop scale (e.g. Siebert, 1984; Takarada et al., 1999; Ui et al., 1986), could be observed. Block lithology is dominated by light grey, sometimes flow-banded, sanidine-porphyritic lava similar to the dominant lithic fraction found in most pumice fall deposits from Rungwe (e.g. Rungwe Pumice, Section 3.2.4). Other lithologies include: (1) syenite, (2) highly vesicular scoriaceous rocks, (3) light grey, almost aphyric lava, (4) clinopyroxene-porphyritic poorly vesicular lava, (5) obsidian, and (6) poorly-sorted indurated breccia blocks. At some locations weathered phenocryst-rich pumices were also identified in the DAD matrix.

Towards Rungwe, the hummocks become larger, of order of tens of meters across, and less conical in shape (Fig. 10g). The topography surrounding the hummocks is characterized by parallel ridges elongated in a roughly E–W direction and typically

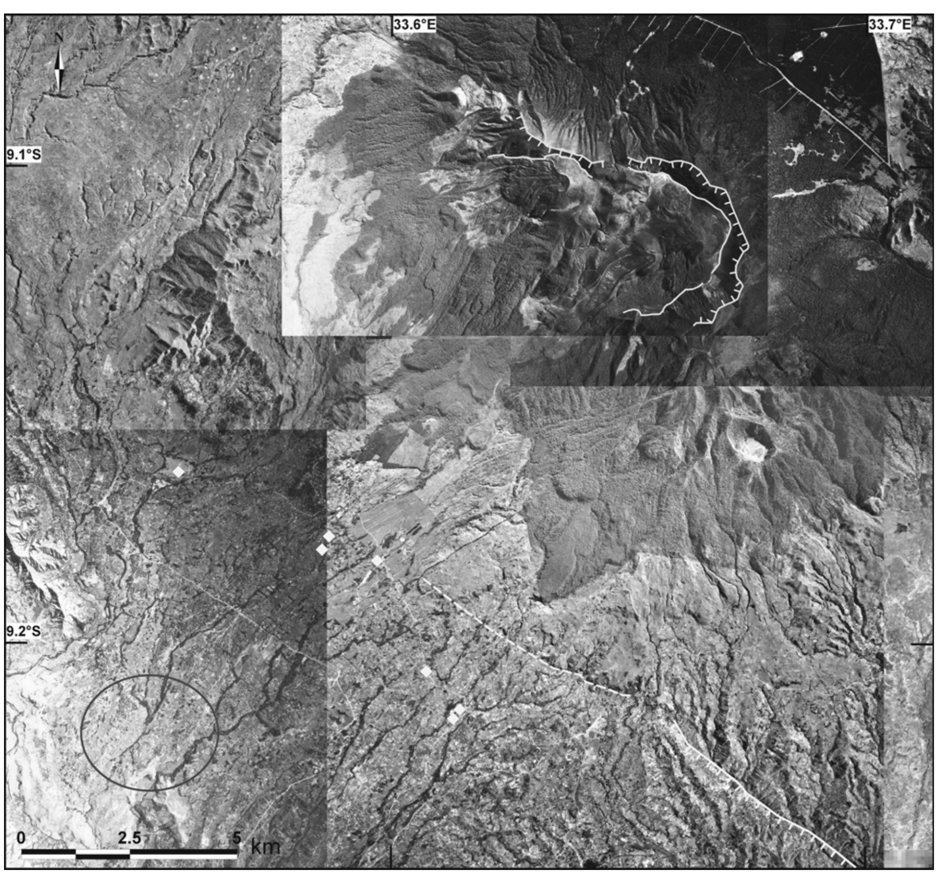

Fig. 9. Air photo view of Rungwe summit depression, showing a collapse scar open to the WSW and several post-collapse domes and cones suggesting significant recent effusive activity. Individual eruptive centres are unnamed. Grey ellipse indicates location of hummocky mound-field associated with debris avalanche deposit, of which other outcrops have also been identified in the field (white diamonds). Dashed line S of Rungwe is the N termination of the NW–SE striking Mbaka Fault (e.g. Fontijn et al., 2010b). Modified after Fontijn et al. (2010a).

Fig. 10. Photographic overview of medial/proximal (a–c) and distal (d–h) Rungwe DAD. (a) NE–SW elongated hummocks/ridges in gently sloping tea estate field; (b) dm-scale bedding towards the top of the DAD; Rungwe Pumice on top, separated by palaeosol (top indicated with black dotted line); (c) poorly sorted DADs in medial/proximal outcrop; (d) hummocky mound-field originally described by Harkin (1960) as lahar deposits; (e) typical shape of a mound, constructed of poorly sorted debris, often covered with large blocks; (f) block showing jigsaw-like cracks; (g) larger, less conical hummocks towards Rungwe; (h) distal cliff of the deposit, ca. 22 km from the source.

a few to ca. 20 m high. The ridges are tens of meters long and tend to end abruptly in a rather flat surrounding terrain. Hence they remind of transverse ridges interpreted to result from flow deceleration (e.g. Dufresne and Davies, 2009). The distal extent of the deposit was traced down to 22 km SW of Rungwe. Here, a clear distal cliff (Ui et al., 2000) of several meters high abruptly ends in a flat plain (Fig. 10h). The collapse height of the deposit, i.e. the vertical distance it travelled, is to a first approximation estimated to be ca. 1.7 km. The maximum run-out distance is ca. 22 km, i.e. the H/L ratio approximates 0.08. So far, no constraints are available on the deposit thickness and volume.

In the more proximal parts of the DAD, roughly 10 km SW of the volcano, tea estate fields reveal the top morphology of the deposit. Ridges and hummocks with an irregular shape consisting of very poorly sorted debris are elongated in a NE–SW direction. The ridges/hummocks typically stand out ca. 5 m above the surrounding landscape which slopes quite gently towards the SW (Fig. 10a).

At several locations between the proximal hummocky tea estate fields and the mound-field, outcrops have been found of very poorly sorted debris deposits showing a lithology similar to that found in the area of the mound-field, including the presence of weathered pumice clasts (Fig. 10c). These deposits tend to have a massive appearance or are made up by metre to several metre thick units, in contrast to deposits interpreted to originate from debris flows found towards the N of Rungwe. In these latter locations, the deposits usually show some cm- to dm-scale parallel to low-angle cross- or wavy bedding, interpreted as emplaced by small debris flows. Only in marginal DAD outcrops is cm- to dm-scale bedding observed towards the deposit top (Fig. 10b).

The DAD is clearly separated from an overlying pumice fall deposit by a brown palaeosol (Fig. 10b). Based on its spatial distribution and typical field characteristics, the overlying pumice deposit is interpreted as the ca. 4 ka Rungwe Pumice (Section 3.2.4). In most locations where both DAD and Rungwe Pumice were found, the pumice deposit was unfortunately either too weathered to allow reliable chemical analyses, or inaccessible for sampling. In any case, there is ample field evidence that the Rungwe sector collapse was not immediately followed in time by a large explosive eruption, suggesting it was not associated with a magmatic eruption (e.g. Belousov et al., 1999; Cortés et al., 2010; Glicken, 1991). Weathered pumice clasts dispersed in the deposit are interpreted as reworked material (i.e. as the source material that collapsed gravitationally to form a debris avalanche flow) like the rest of the debris matrix and blocks.

In one distal location ca. 22 km SW of Rungwe, deposits interpreted to represent a second, older voluminous debris avalanche with similar lithological characteristics were found. Both deposits are separated by a palaeosol. Radiocarbon dating of this soil yields a calibrated age of 22.3–28.1 ka cal BP (2σ uncertainty; own data by K.F. and G.G.J.E.), providing a maximum age for the younger Rungwe DAD. The age of the overlying Rungwe Pumice deposit, i.e. ca. 4 ka (Fontijn et al., 2010a), constrains the possible age range of the uppermost Rungwe DAD to approximately 4–25 ka BP.

A key finding from systematic field exploration is thus that Rungwe volcano experienced at least two major flank collapses in the past few tens of thousands of years, generating debris avalanche flows energetic enough to travel more than 20 km, to scale up the steep topography of the rift valley wall to the SW and to emplace DADs still several meters thick.

3.2.4. Rungwe – explosive eruptions

Rungwe was possibly dominated by basaltic, phonolitic and trachytic effusive activity until its collapse (Harkin, 1960). The oldest dated Rungwe lavas have a WR K–Ar age of 0.25 ± 0.01 Ma (Fig. 3b; Ebinger et al., 1989), but do not represent the oldest Rungwe activity. Other lava flow deposits from the southernmost units found on the lower flanks of the volcano yield a WR K–Ar age of 49 ± 1 ka (Fig. 3b; Ebinger et al., 1989). Post-collapse activity includes both effusive and explosive activity from silicic lava domes, tephra cones and explosion craters visible on aerial photos of the Rungwe summit region (Fig. 9). No systematic field-based physical volcanology or petrochemical study has yet been undertaken within this vent constructs filled avalanche crater area. No radiometric data exist for any of these post-collapse structures.

Harkin (1960) described cream-coloured pumice deposits that he thought originated from Rungwe, covering almost the entire RVP area. Although he attributed these to several "*pumice showers*" he did not map the different pumice deposits in any detail, systematically, or as distinct tephra units. Also in palaeo-anthropological studies in N Malawi and SW Tanzania, several volcanic ash and pumice beds attributed to Rungwe volcano were recognized, but not described separately (Clark et al., 1970; McBrearty et al., 1984; Wynn and Chadderdon, 1982). Carrying out such field research and subsequently further characterizing field samples in sedimentological or analytical laboratories, are major and time-intensive undertakings that were well beyond the scope of Harkin's pioneering work in the 1950s, or of palaeo-anthropological investigations. Developing these aspects of fundamental research have been major focus areas for the research presented by Fontijn et al. (2010a), who described the Holocene explosive eruptive history of Rungwe.

The most important deposit in the Holocene Rungwe record is the ca. 4 ka Rungwe Pumice, traceable over more than 1500 km^2 (Fig. 11). It has been geochemically correlated to a pumice and ash bed found in Lake Masoko (Fig. 4; Barker et al., 2003; Fontijn et al., 2010a; Gibert et al., 2002). Ash beds with an interpolated age similar to that of the Rungwe Pumice as defined by radiocarbon dating of palaeosols underneath the deposit (Fontijn et al., 2010a), are also found in Lake Malawi (Fig. 4; Barker et al., 2007; Barry et al., 2002; Johnson et al., 2002; Williams et al., 1993), down to a distance of at least 115 km SSE of Rungwe volcano. The Rungwe Pumice is a massive, lithic-poor, white to cream-coloured pumice lapilli breccia deposit which is reversely graded at the base. The pumice lapilli are of trachytic composition (Fig. 8) and phenocryst-poor (<5 vol.%), with phenocrysts of sanidine, biotite, clinopyroxene (diopside), titanomagnetite, ilmenite, amphibole, plagioclase, apatite, titanite and haüyne. The latter mineral only occurs in the Rungwe Pumice deposit and not in other Rungwe deposits. Due to its characteristic blue colour, the haüyne is a useful marker in the field. Some banded pumices occur, showing a slightly different mineralogical composition (more plagioclase and amphibole). The banded pumices are thus interpreted as the result of magma mingling. The deposit seems to be compositionally zoned with slightly more evolved compositions at the base of the deposit compared to the top (upwards decreasing SiO_2, Zr, increasing MgO, TiO_2, CaO).

The Rungwe Pumice was comprehensively documented both in the field and the laboratory. The extensive dataset enabled to physically model the eruptive parameters of the eruption and revealed that the Rungwe Pumice is a rare case of a Plinian eruption that happened in nearly wind-free conditions (Fontijn et al., 2011). This is consistent with the spatial distribution of the deposit, e.g. the nearly circular isopach contours (Fig. 11). Empirical modelling using models proposed by Carey and Sparks (1986) and Pyle (1989) suggests a maximum eruption column height H_T of 30.5–35 km. The wind speed during the eruption is constrained to a first order by the model of Carey and Sparks (1986), i.e. based on isopleths of maximum lithic size in every location, to 2.5–8.5 m/s. The H_T estimates are also consistent with inversion modelling on individual grain size classes with the analytical TEPHRA2

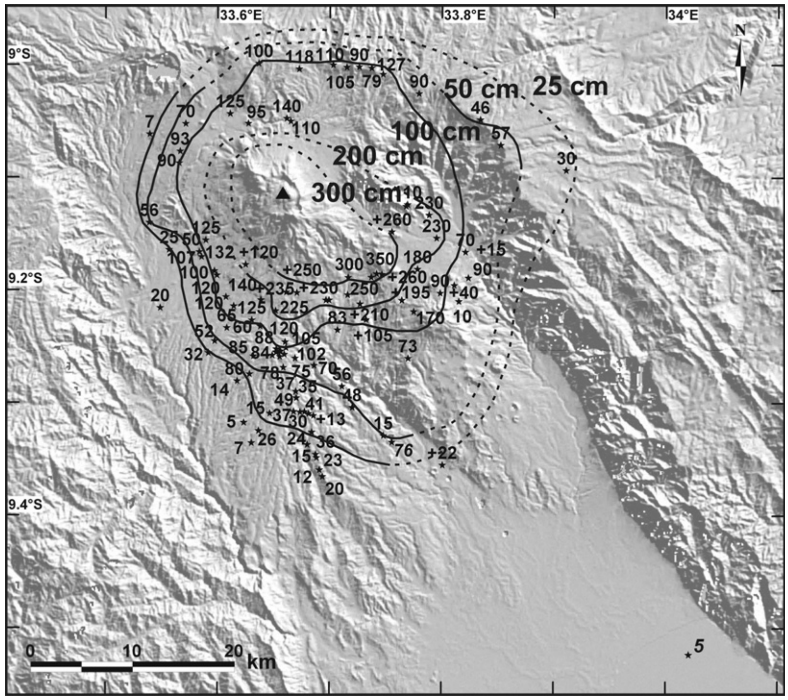

Fig. 11. Rungwe Pumice isopach map; deposit thickness values in cm. Parts of isopach contours which are interpreted tentatively are indicated with dashed lines. Values in italics refer to less well constrained estimates or non-primary thicknesses. The southernmost data point, in N Lake Malawi, is a rough estimate. Vent location is tentatively indicated with a black triangle placed centrally on the Rungwe summit region. Modified after Fontijn et al. (2010a).

model (Bonadonna et al., 2005; Connor and Connor, 2006; Volentik et al., 2010), suggesting an H_T of 33 ± 4 km. The total range of estimates of maximum eruption column height derived from both empirical and analytical modelling, i.e. H_T 32 ± 5 km, corresponds to a range for peak mass discharge rates of $2.3–6.0 \times 10^8$ kg/s (Wilson and Walker, 1987).

The erupted volume is estimated based on the thinning characteristics of the deposit presented on a plot of log(thickness) vs. $(\text{area})^{1/2}$, where the area is the enclosed isopach area of the corresponding thickness (Bonadonna et al., 1998; Bonadonna and Houghton, 2005; Pyle, 1989). The (minimum) deposit volume estimate is constrained at 3.2–5.8 km^3. With an average deposit bulk density of 343 kg/m^3, this volume estimate corresponds to a minimum total erupted mass of $1.1–2.0 \times 10^{12}$ kg. Inversion modelling of mass/area values in each location with TEPHRA2 results in an erupted mass estimate of 1.1×10^{12} kg, consistent with the empirically derived estimate based on the deposit thinning characteristics. Both the spatial distribution and the volume estimate of 3.2–5.8 km^3 of the Rungwe Pumice are consistent with the interpretation as a Plinian fall deposit. The Rungwe Pumice classifies as a VEI 5 event (Newhall and Self, 1982). The comprehensive documentation of the Rungwe Pumice by Fontijn et al. (2011) makes it the first Plinian-style deposit on the African continent to be systematically mapped or physically modelled.

Close to the NW shore of Lake Malawi, ca. 95 km SSE from Rungwe, charcoal flecks immediately underlying a ca. 30 cm thick volcanic ash bed are radiocarbon dated at 3300 ± 140 yr BP (Clark et al., 1970; Haynes et al., 1967). Although it is not certain that this thickness reported by Clark et al. (1970) is the primary depositional thickness, the significant amount of ash deposited in a location this far from Rungwe, and the broadly similar radiocarbon age of underlying charcoal leads us to suspect that this volcanic ash corresponds to the Rungwe Pumice. Also on the Kitulo Plateau, in a location ca. 13 km N of Rungwe, a palaeosol buried by a volcanic ash deposit attributed to Rungwe, was radiocarbon dated at 3920 ± 80 yr BP (Clark et al., 1970; Haynes et al., 1971). Although neither thickness nor more detailed descriptions of the ash bed are reported, it probably corresponds to the Rungwe Pumice as well. Two more volcanic ash deposits occur on top of the presumed Rungwe Pumice in this location, all separated by palaeosols dated at 3200 ± 100 yr BP (middle soil) and 2800 ± 400 yr BP (top soil; Clark et al., 1970; Haynes et al., 1971). Without any further lithological and/or geochemical constraints, it is unclear how these deposits correlate with the Holocene stratigraphy of explosive Rungwe eruptions presented by Fontijn et al. (2010a) (Fig. 7).

The second most important deposit in the Rungwe record is that of the ca. 2 ka old Isongole Pumice (Fig. 7), a (phonolitic) trachytic (Fig. 8), cream-coloured pumice lapilli breccia deposit showing significant primary grain size variations in its upper half to upper two thirds. Pumice lapilli are phenocryst-poor with a phenocryst assemblage similar to that of Rungwe Pumice, except for the absence of haüyne. In contrast to Rungwe Pumice, Isongole Pumice displays characteristic lithic content variations: it is lithic-rich (up to 30%) in the lower half, and lithic-poor in the upper half. Apart from trachytic lava clasts, widely abundant in the Rungwe deposits, angular ash to small lapilli size obsidian clasts ("obsidian chips") also occur. Based on the spatial distribution, and volume estimate of the lower, massive part of the deposit (0.25 km^3), the Isongole Pumice is interpreted as a VEI 4 event. The eruption is interpreted as a blast through a pre-existing lava dome or cryptodome during an initial phase of vent conduit generation to account for abundant obsidian lithics in the lower part of the deposit (Fontijn et al., 2010a).

Three more Rungwe deposits have been described by Fontijn et al. (2010a), and were all dated at less than 1.5 ka by radiocarbon dating of palaeosols: Ngumbulu Tephra, Aphyric Pumice and Kizungu Tephra (Fig. 7). The Ngumbulu Tephra is a reversely graded, very lithic-poor coarse ash to small pumice lapilli deposit of trachytic composition (Fig. 8). Pumices are phenocryst-poor with phenocrysts of sanidine and clinopyroxene. The Kizungu

Tephra is a normally graded, very lithic-poor coarse ash to small pumice lapilli deposit of phonolitic–trachytic composition (Fig. 8). Pumices are phenocryst-poor with phenocrysts of sanidine and biotite. Both Ngumbulu and Kizungu Tephra represent deposits of moderately explosive eruptions.

The Aphyric Pumice is somewhat exceptional in the Rungwe record as the only Rungwe deposit with a (trachytic) phonolitic composition (Fig. 8), and with almost aphyric pumices. The chemical composition and aphyric nature of pumices reminds of the Ngozi deposits, but field evidence strongly points to a Rungwe origin for the Aphyric Pumice. The deposit occurs as a reversely graded, lithic-poor pumice lapilli breccia and was chemically correlated to an ash bed in the Masoko sediment core dated at 1.2 ka cal BP (Fig. 4; Barker et al., 2003; Fontijn et al., 2010a; Garcin et al., 2006; Gibert et al., 2002).

3.2.5. Kyejo

The third large RVP volcano is Kyejo (volcano 0202-17= in the GVP database: Siebert et al., 2011; alternative spelling: Kiejo, Kieyo), thought to consist dominantly of lava flow units with (alkali) basalt–basanite–tephrite and phonolitic trachyte–trachyandesite compositions (Crabtree and Chesworth, 1992; Harkin, 1960). Its dominantly effusive eruptions are also accompanied by low-intensity and low-magnitude explosive activity compared to Ngozi or Rungwe – although locally significant explosion craters can be seen at its summit (Fig 12). Kyejo belongs to the "Kyejo cluster" of volcanic vents (Fontijn et al., 2010b), characterized by numerous satellite vents to Kyejo, mostly in the form of spatter-scoria cones, especially S of the volcano (Fig. 2). Kyejo has a slightly NW–SE elongated base of ca. 5×7 km^2. The summit rises to a peak elevation of 2175 m asl, ca. 600–700 m above its base. Activity at Kyejo is thought to have started in the mid-Pleistocene (oldest lava flow deposit dated at 0.42 ± 0.03 Ma by WR K–Ar dating; Ebinger et al., 1989).

The Sarabwe tephrite lava flow eruption is the most recent and only historically recorded RVP eruption. The eruption originated from two spatter-scoria cones, Sarabwe and Fiteko, located along a NW–SE trending fissure on the upper NW flank of Kyejo. Harkin (1960) dated the eruption at approximately 1800 AD, based on enquiries among local inhabitants that revealed information passed down through previous generations. According to these oral accounts, the Sarabwe and Fiteko cones were synchronously active and the eruption lasted for 3 days. The lava flow travelled ca. 8 km downhill (Fig. 12). As some more, smaller cones occur between the Fiteko and Sarabwe cones, it seems likely that the Sarabwe eruption was a fissure eruption with not only Fiteko and Sarabwe, but also these other cones active at the same time. What is interpreted by Harkin (1960) as the Sarabwe cone, also appears to be a cone breached by a lava flow that is older than the 1800 AD Sarabwe lava flow. The former lava flow deposit is of alkali basalt composition (Crabtree and Chesworth, 1992), has levees which are several metres high and is covered with a dense forest, in contrast to the 1800 AD tephritic Sarabwe lava flow deposit seen on the lower Kyejo flanks (Fig. 12). The Sarabwe eruption is the only RVP eruption for which historical, though non-written and somewhat ambiguous, accounts exist. Apart from this eruption, the recent eruptive history of Kyejo remains unknown.

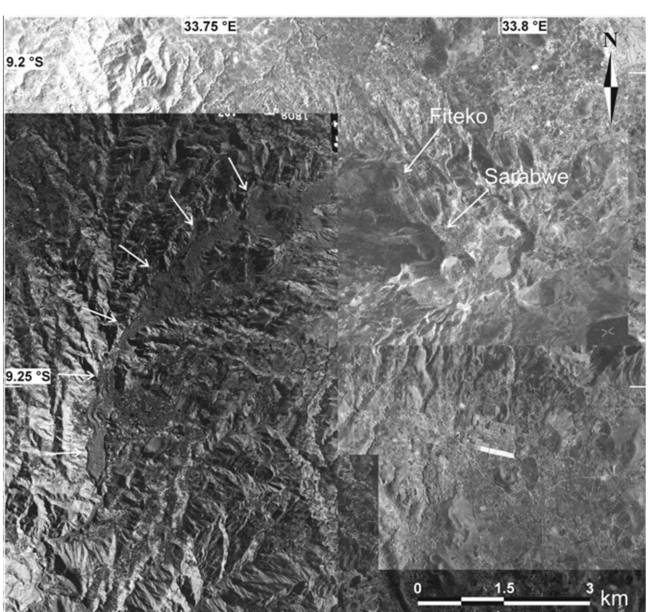

Fig. 12. Air photo view of Kyejo volcano, with the 1800 AD Sarabwe flow deposit visible on the W side (indicated by white arrows), originating from two cones, Sarabwe and Fiteko on the NW flanks of the volcano. The cone indicated as Sarabwe is the one described by Harkin (1960), which is probably not the one that fed the 1800 AD lava flow.

3.3. Petrogenesis

In a geochemical study of mafic RVP lavas, including both effusive products from the *Younger Extrusives* volcanoes (Rungwe and Kyejo) and from the *Older Extrusives* centres (Ngozi, Katete and Tukuyu), Furman (1995) concluded that the source for RVP lavas is a garnet peridotite, mildly metasomatised by CO_2-rich and/or mafic silicate fluids. Many RVP lavas are interpreted to have formed by very low degrees of melting (up to $\sim$5%), with the lowest degrees for nephelinite lavas found only at Kyejo volcano. Low degree and high-pressure (>30 kbar) partial melting of mantle material was also suggested by Ivanov et al. (1998). Once formed, the mafic melts are thought to have undergone differentiation and mixing processes at moderate pressures (Furman, 1995). For Kyejo in particular, compositional variations seen among mafic lava flow units are ascribed to a complex mechanism of olivine accumulation, olivine and clinopyroxene fractionation, and crustal contamination (Crabtree and Chesworth, 1992).

4. Discussion

4.1. Volcano-tectonic interactions

The division of volcanic activity in three stages since ca. 9 Ma ago is based on a handful of studies accompanied by a few tens of radiometric dates covering the entire region. Hence the separation between stages 1 and 2, in particular, should be treated with caution (Fig. 3a). According to the existing geological map, largely based on the map produced by Harkin (1960), the deposits of the first two stages do occur in different RVP sectors. Volcanic rocks of the first stage of volcanism (Late Miocene) mostly occur on the rift shoulders of the Lupa Block (Rukwa Rift–Usangu Basin) and the Kitulo/Elton Plateau (Malawi Rift–Usangu Basin). They are associated with the first phases of development of the triple junction between the Rukwa, Malawi and Usangu Basins (Fig. 2). Deposits of the second stage (Late Pliocene–Early Pleistocene) occur all over the RVP in the accommodation zone between the rift basins. Deposits of the third stage of volcanic activity (Mid Pleistocene–Recent) occur in a much more narrowly defined zone which may consistent with a tectonic regime that has a stronger control upon volcanic activity location than the regime during the first two stages of volcanism. How this control over the volcanic activity can be accounted for, e.g. including the effect of volcano load or rotations caused by propagating faults (e.g. Beutel et al., 2010;

Ebinger et al., 1989, 1993) is however beyond the scope of this review.

The strong tectonic control upon recent volcanism, especially on the location of Ngozi and Rungwe volcanoes, and the fact that both volcanoes show geomorphological evidence of past destabilization events, led Fontijn et al. (2010b) to conclude that faulting affects RVP volcanoes and could potentially lead to significant hazards. At Rungwe, ample evidence exists for a sector collapse event generating a debris avalanche travelling down to ca. 22 km SW of Rungwe. The timing of this event is as yet crudely constrained between ca. 4 and 25 ka cal BP. Field evidence also suggests a second, older, DAD. Sector collapses are not necessarily triggered by tectonic activity, but could be associated with a magmatic eruption, as was the case of Mount Saint Helens in May 1980 (Lipman and Mullineaux, 1981). However, in the case of Rungwe, there is no evidence at all to suggest that at least the younger of the two events was associated with a magmatic eruption. The clear separation of the DAD from the overlying pumice fall deposit (Rungwe Pumice) by a palaeosol, is in favour of an interpretation as a collapse without an associated magmatic eruption, e.g. an "Unzen-type" collapse triggered by an earthquake (Ui et al., 2000). Furthermore, Rungwe is likely undercut on its SW lower flank by the Mbaka Fault, originally a normal fault which acts as a strike- or oblique-slip fault under the current stress regime of NW–SE compression (Delvaux et al., 1992; Ring et al., 1992; Brazier et al., 2005; Delvaux and Barth, 2010). High steep volcanoes with strike-slip faults passing near their foot have been found from analogue modelling to be unstable, and to be potentially affected by flank collapse as a result of cumulative sub-volcanic fault motions. If the undercutting fault is located off the volcano's central axis, as is the case for the Rungwe–Mbaka system, long-term strike-slip faulting could cause edifice failure in a direction perpendicular to the fault strike (Wooller et al., 2009). Predictions from analogue modelling by Wooller et al. (2009) fit closely with the Rungwe sector collapse geometry. In combination with the interpretation of a collapse in absence of an associated magmatic eruption, it is suggested here that flank instabilities at Rungwe are closely linked to tectonic activity. Further research on the DADs is needed to constrain processes generating the debris avalanches and to constrain the timing of the events.

Like Rungwe, Ngozi is also located at the intersection of major faults and lineaments. The irregular morphology of the caldera, e.g. the plateau in the N part and the notch in the S rim, suggests that the Ngozi edifice is unstable and prone to destabilization of the caldera walls, likely in close interaction with earthquake activity (Fontijn et al., 2010b). Earthquakes are relatively common in the RVP region, with 43 $M \geqslant 4.5$ events since 1973 within a search radius of 200 km around Rungwe volcano (USGS Earthquake Database, 2011; http://earthquake.usgs.gov/earthquakes/eqarchives/epic). Despite significant location errors of order of tens of kms in this database, the distribution of earthquakes suggests that they dominantly occur along faults associated with the Rukwa and Malawi Rifts, e.g. the 2009 Karonga earthquakes in N Malawi including four $M > 5.5$ events (Biggs et al., 2010). This is also evidenced by data gathered from a seismic network operated between June 1992 and December 1994, during which time 199 local earthquakes were measured between Lake Rukwa and Lake Malawi, with most events centred along the borders of the SE Rukwa basin (Camelbeeck and Iranga, 1996). Apart from potentially causing destabilization of volcanic edifices, earthquakes can also cause unrest at volcanoes or trigger eruptions (e.g. Delle Donne et al., 2010; Eggert and Walter, 2009). Tectonic earthquakes of magnitude $M \geqslant 4.8$ are capable of triggering eruptions at volcanoes at a distance less than 10 times the fault length (Lemarchand and Grasso, 2007). Such an earthquake–eruption interaction is statistically uncommon (0.3%) but is not unlikely in the RVP where a strong control of tectonic activity exists upon volcanism (Fontijn et al., 2010b).

4.2. Volcanic hazards

Given the frequency of explosive volcanic eruptions, they are expected to occur mostly in the absence of tectonic earthquake triggering (Fontijn et al., 2010a). The Rungwe Holocene stratigraphic record constrains an absolute minimum eruptive frequency of at least one explosive eruption every ca. 500 years. The intensity/style of Rungwe explosive eruptions ranges from violent Strombolian to Plinian (Fontijn et al., 2010a). The most intense and largest-magnitude eruption in the Holocene record so far is the ca. 4 ka Rungwe Pumice, a Plinian eruption in nearly wind-free conditions (Fontijn et al., 2011). A characteristic feature of this Rungwe Pumice deposit, and in fact of all tephra fall deposits from Rungwe, is that no associated PDC deposits are found. In the case of Rungwe Pumice, two factors can be invoked for this lack of PDCs: (1) the extremely low pumice density, of order 400–450 kg/m^3, contributing to a plume density low enough to prevent column collapse (Fontijn et al., 2011) and (2) the high mass discharge rate was not through a central vent but distributed along many vents along arcuate narrow fractures inherited by collapse events that generated the large avalanche caldera at Rungwe's summit. The dataset collected by Fontijn et al. (2011) for the Rungwe Pumice makes this deposit one of the most closely documented prehistoric Plinian deposits worldwide, and the first one in Africa.

The absence of a clear caldera associated with the Rungwe Pumice despite an erupted volume of 1.4–2.5 km^3 DRE is consistent with a moderately deep magma chamber, i.e. of order of 5–6 km below the summit. This is also consistent with biotite phenocrysts being present in the pumice clasts, requiring a threshold magma chamber depth and pressure to be stable. The biotite appears fresh, i.e. does not show any sign of breakdown rims that would be expected to result from a shallow magma chamber and/or pre-eruptive degassing, and is indicative for fast magma ascent rates before the eruption (Fontijn, 2011).

The number one volcanic hazard at Rungwe directly related to volcanic eruptions appears to be tephra fall. In an income-poor region like Rungwe where the majority of the houses have either grass-thatched or flat corrugated iron roofs, 10–20 cm of ash fall would be sufficient for the roofs to collapse (USGS, 2011). Although the impact of ash fall upon agriculture may be limited over time, a few cm of ash fall destroying crops could cause serious problems for local food supply and temporarily reduce the small incomes from agriculture that families depend upon. Furthermore, mudflows can be generated on steep ash-covered slopes during the rainy seasons.

From air photo observations it is clear that lava flows have also occurred at Rungwe in its recent past. Some of these flows might be associated with explosive eruptions that were identified in the stratigraphic record. Though challenging because of vegetation growth, detailed field mapping in the summit region will help understand the relationship between effusive and explosive eruptions at Rungwe. The distribution of post-collapse lava flows from Rungwe appears largely limited to the summit depression region where the local population is not immediately affected – apart from few indigenous people collecting timber wood and honey from beehives.

Ngozi has known at least two major, regional-scale eruptions in the Holocene, that are both thought to have contributed to the formation of the present-day caldera: the ca. 10–12 ka Kitulo Pumice and the Ngozi Tuff (Fig. 7). Only few on-land outcrops of Kitulo Pumice were found as yet but it is interpreted to be present in most sediment cores drilled in RVP-surrounding rift lakes, i.e. Lake Malawi, Lake Rukwa and even Lake Tanganyika. The current data are consistent with a major Plinian-style eruption generating a fallout deposit covering the entire RVP. This eruption possibly also generated PDCs although field observations are not conclusive at present.

The Ngozi Tuff, thought to correlate with the 1674 ± 13 AD A1 ash layer found in Lake Malawi cores (Barry et al., 2002; Williams et al., 1993), is interpreted as PDC deposits covering a vast area S of Ngozi and also partly constructing the S caldera wall. The fact that Ngozi has known ignimbrite-forming eruptions strikingly contrasts with the eruptive behaviour of Rungwe, characterized by eruptions generating pyroclastic fallout only, and is significant in terms of hazards. PDCs are known to be much more destructive than tephra fallout and able to destroy everything they pass on their way. Areas that have been impacted by PDCs are likely to be affected again in future eruptions. In the case of Ngozi, one area likely to be impacted by PDCs, is the area down to tens of kms S of the caldera. Today, this is a very remote and income-poor area where people largely depend on the harvest of Irish potatoes and beans for their daily survival. Another future potentially impacted area is the fast growing city of Mbeya, 15 km NW of Ngozi.

The eruptive behaviour and frequency of Ngozi is poorly known and should be studied in more detail. Field observations S and W of the Ngozi edifice suggest much more tephra deposits to occur in between Kitulo Pumice and Ngozi Tuff. Also N of the volcano more key outcrops remain to be studied. Studying these key outcrops is crucial to map and quantify geohazard risks threatening the city of Mbeya: notably PDCs, tephra fallout and mudflows.

At present, the Holocene eruptive record reconstructed for Rungwe and Ngozi is interpreted to be biased towards larger-scale eruptions, and missing out on smaller-scale eruptions generating relatively minor quantities of volcanic ash. Results are in the first place dependent on the preservation of deposits, both on land or in lakes. Although the completeness of the eruptive record registered in lakes is strongly dependent on the location, i.e. direction and distance, of these lakes with respect to the volcanic source, lake sediment cores do provide the opportunity to obtain a record spanning a much longer time period than on-land sections alone. In the case of Rungwe volcano, the Masoko core significantly underestimates the late Holocene eruptive frequency: two tephra layers (Aphyric Pumice and Rungwe Pumice) are recorded in the lake instead of 5–8 found on land for the same period (Figs. 4 and 7). Five more Early–Mid Holocene tephra layers are however found in the Masoko core, which were not found – yet – in on-land sections, the only exception being the Kitulo Pumice from Ngozi. The currently reconstructed eruptive history could be significantly extended in time in terms of eruptive frequency by chemical fingerprinting of tephra layers found in several lakes in and around the RVP, and assigning them to a source volcano, especially by the use of incompatible trace elements (Fig. 5). So far, volcanic ash occurrence in sediment cores has been mentioned with regards to timing of eruptive events, but no systematic studies have been performed on the geochemistry and thorough correlation of ash beds between different cores. Chemical fingerprinting would help to strengthen correlations made on the basis of time constraints, and to discriminate between Ngozi or Rungwe origins for yet uncorrelated felsic ashes found in sediment cores. This information is essential in understanding the minimum eruptive frequency at both volcanoes.

One possible approach to enhance the resolution of the Holocene stratigraphic record observed in on-land sections is manual on-land coring in order to obtain an undisturbed deposit sequence. These cores can then be scanned for magnetic susceptibility to detect (micro)tephras, similar to the method used for lake sediment cores. This method has recently been presented by Legendre et al. (2010), who identified several previously unknown tephra deposits from La Soufrière volcano on Guadeloupe in the last 8000 years, doubling the previously suspected eruptive frequency. To enhance the quantification of the eruptive frequency, manual coring should be performed at locations where the thick Rungwe Pumice deposit does not occur at the surface, i.e. N or NE of the summit; and above the Rungwe Pumice.

Currently, hardly anything is known about the eruptive history of Kyejo except for a rather incomplete account of the effusive Sarabwe eruption dated at ca. 1800 AD (Harkin, 1960). Although Kyejo is thought to be flow-dominated, several dark-coloured ash layers are recorded in the Masoko core, which are likely associated to relatively small-scale explosive eruptions from Kyejo or its satellite vents.

Despite very sparse archaeological findings in the Rungwe area (Clark et al., 1970; McBrearty et al., 1976, 1984; Wynn and Chadderdon, 1982), there is some evidence to suggest that there was human occupation in the Rungwe region during at least the Late Stone Age (Kala occupation and Kiwira industry) although it is not clear whether the occupation was continuous until historic times (Wynn and Chadderdon, 1982). Throughout history, from the Late Stone Age until today, communities, if present, may have been significantly affected by major explosive eruptions at Rungwe or Ngozi. In modern history, even though the most recent eruptions at both volcanoes occurred only a few hundred years ago, only very few and poorly known oral stories seem to exist today among local Nyakyusa or Safwa tribes about special events occurring at Rungwe or Ngozi volcanoes. One story mentions the god of Rungwe throwing a stone towards Ngozi, leaving a hole in the ground, which is presently filled by the caldera lake (Wilbert Mtafya, personal communications, 2011). This is consistent with collective memory of caldera-forming eruption(s) at Ngozi, dated here at 10–12 ka BP and at 1674 ± 13 AD.

4.3. Volcano monitoring

The tectonic–volcanic interplay, the Holocene record of explosive eruptions, and the geomorphologically fresh lava flows and volcanic constructs at both Rungwe and Kyejo volcanoes, suggest that at least minimal continuous tectonic and volcano monitoring in the RVP is recommended. Further research to more accurately define the eruptive frequency and behaviour of all three major RVP volcanoes, i.e. Ngozi, Rungwe and Kyejo, and to quantify geohazard risks, is advised as complementary to developing an effective monitoring system.

The heart of any ground-based volcano monitoring system is a network of broadband seismometers. In the case of Rungwe, it may be suspected that eruptions are not preceded by a persistent period of seismic unrest, as the magma chamber is expected to be fairly deep (absence of caldera, presence of biotite and amphibole in phenocryst assemblage), and petrological evidence (absence of biotite breakdown rims) indicates a systematic fast magma ascent of order of only a few hours to days. This may or may not be similar to the case of the Hekla volcano in Iceland, where volcanic tremor starts quasi-synchronously with eruptions (Soosalu et al., 2003; Soosalu and Einarsson, 2004). Seismic monitoring should thus be complemented with other techniques. A better knowledge of the magma chamber system, based on both petrological data (e.g. more accurate assessment of pre-eruptive conditions and magma ascent rates of different Rungwe magmas) and geophysical surveys, would be helpful in defining the most optimal monitoring techniques.

To record pre-eruptive deep system variations, regular soil CO_2 flux measurements are expected to be most efficient in the RVP. These measurements have the advantage of being relatively cheap and can be carried out by trained local people. Other potential low-cost approaches include regular visual observation surveys at the summit of the volcanoes and regular hot spring temperature measurements.

4.4. Geohazard risk mitigation and resource benefits

To assess volcanic hazards further towards geohazard risk mitigation, it is essential to share scientific findings and their implications with local scientists, authorities and communities. In less industrialized countries affected by extensive income poverty, such as Tanzania, local authorities struggle mostly with socio-economic, poverty-related issues. Hence assigning resources to the study and mitigation of tectonic or volcanic hazards is not considered a priority. In Tanzania today, there is currently an expertise shortage in technical and specialized volcanology, and yet the country has historically active and hazardous volcanoes, e.g. Ol Doinyo Lengai and Meru, as well as several Late Quaternary volcanic centres that are likely to erupt again in the future, e.g. the RVP volcanoes and Kilimanjaro.

The RVP volcanoes exhibit unique features that are of profound scientific interest to advance our understanding of how volcanic systems and eruptions work (e.g. the striking absence of PDCs in Rungwe's recent deposit record; the significant explosive nature of low-to-moderate-viscosity magmas with implications for volatile budgets and magma ascent rates; the strikingly contrasting explosive behaviour at Ngozi vs. Rungwe vs. Kyejo). More detailed fundamental studies of the RVP tectono-magmatic system, and indeed of many volcanic regions in Africa (e.g. eruption frequency–magnitude relationships, magma chamber recharge rates, earthquake recurrence intervals, etc.), are not only critical to assess and mitigate potential geohazards, but will ultimately contribute to sustained geohazard mitigation strategies (ITCP, 2009).

The ecotourism developed at Kilimanjaro and Ol Doinyo Lengai uniquely illustrates how African volcanoes have a potential as an income-generating, touristic resource that could be in the first place a direct benefit for local communities (as well as for international tour operators) rather than a short-term geohazard. The development of sustainable and safe ecotourism is however ideally combined with good knowledge/research/monitoring of the volcano.

In the Rungwe region, volcanic resources (e.g. volcanic raw materials, ecotourism, hot springs, volcano-hosted rainforest ecosystems and key plantations) are already harnessed locally. The Mbeya Cement Company uses volcanic ash and lime from the Songwe hot springs as an additive in the production of cement. In remote villages, pumice and ash are also used by local people for brick production to construct houses. CO_2 degassing from vents near the foot of Kyejo is bottled commercially for use in soda drinks. In this case the CO_2 is not only harnessed as an economic benefit, but the potential risk of CO_2 accumulation to lethal concentrations is also removed. Indirectly related to the volcanic activity, the fertile soils and local climate allow the development of vast tea plantations. Around Rungwe, many smallholder tea farmers are united in a cooperative able to compete against large companies. In the last decade or so local initiatives have been set up that try to generate an income from ecotourism, e.g. the Bongo Camping in Kibisi (Tukuyu) and Rungwe Tea & Tours in Tukuyu. Despite all these efforts, the harnessing of volcanic resources in Rungwe is still modest, and local communities could potentially benefit much more from their volcanoes.

By helping people benefit from the volcanic resources today, it is expected they will gain a greater appreciation of their local volcanoes and start to perceive the volcanoes from different perspectives, including becoming more aware of the possibilities the volcano has to offer, but also of the potential hazards. Enhancing geohazard risk awareness at all levels, local communities, authorities and scientists, is at least as crucial to geohazard risk mitigation as mapping and assessing hazards well before an eruptive crisis.

To mitigate geohazard risks as efficiently as possible, the existing eruptive record could be exploited to derive hazard zonation maps. These maps should be combined with socio-economic studies to evaluate risks associated with specific volcanic hazards in the RVP. Geohazard awareness among local communities could be gradually developed by educational programmes, but also by setting up initiatives in which local people can benefit from the volcanoes by harnessing the natural resources.

5. Conclusions

This paper presents a review of the current volcanological knowledge that now exists for the Rungwe Volcanic Province in SW Tanzania, characterized by three large central volcanoes, Ngozi, Rungwe and Kyejo. The RVP is located at the intersection of the Western and Eastern Branches of the East African Rift System, and at both regional and local RVP scale, a strong control of tectonic activity acts upon volcanism. The basis of volcanological studies in the RVP region was laid by Harkin (1960) who provided a framework for RVP-scale general volcanic stratigraphy, based on field relationships and petrological studies. In past decades several sediment cores were drilled in RVP-surrounding rift lakes as well as in the Masoko crater lake. These provided invaluable records of tephra occurrence in the last few tens of thousands of years. Only recently, attempts have been made to correlate some of the ash beds to widespread tephra deposits found on land, in a reconstruction of the Holocene record of explosive eruptions from Rungwe and Ngozi volcanoes. The reconstructed record so far indicates that both Ngozi and Rungwe volcanoes have known Plinian-style eruptions in their Holocene past. Rungwe also experienced at least two sector collapses generating debris avalanches. The eruptive history of Kyejo volcano, the only RVP volcano with a clear oral account of an eruption at ca. 1800 AD, remains unknown. As the eruptive history of a volcano is the first essential step towards thorough geohazard assessment and mitigation efforts, it is highly recommended that further stratigraphic, volcanological and quantitative risk assessment studies in combination with low-cost continuous volcano monitoring are undertaken, in order to gain insights into the dynamics of the RVP volcanic system.

Acknowledgements

This review is for a significant part based on the PhD work of K.F., together with G.G.J.E. supported by the Belgian Research Foundation – Flanders (FWO – Vlaanderen). Many people have assisted in many different ways and are greatly acknowledged: Damien Delvaux, Edista Abdallah, Shimba Kwelwa, Shabane Sangalala, Gabriel Mwakyambiki, the people from Bongo Camping and Rungwe Tea & Tours, Marlina Elburg and Patric Jacobs. Bert Van Bocxlaer is thanked for his comments on the section dealing with palaeontology in this paper. Permissions for field work were provided by the Tanzanian Commission for Science and Technology (COSTECH). We kindly thank Pat Eriksson for suggesting this review. Reviews by Cindy Ebinger and Nils Lenhardt were greatly appreciated. This work is a contribution to the Rungwe Environmental Science Observatory Network (RESON, CORUS6125, University of Dar es Salaam).

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