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PHYSICAL VOLCANOLOGY, GEOMORPHOLOGY, AND COSMOGENIC ^{3}HE DATING OF THE YOUNGEST KIMBERLITE VOLCANOES ON EARTH (THE HOLOCENE IGWISI HILLS VOLCANOES, TANZANIA

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INTRODUCTION

The Igwisi Hills kimberlite volcanoes (IHV; Sampson 1953; Reid et al. 1975; Dawson 1994) are thought to be very young (Quaternary) but no reliable radiometric dates have yet been published. The next youngest kimberlite rocks are Eocene-Oligocene in age. Because of their youth, the IHV still have surface rocks and volcanic constructs. Kimberlite pyroclastic rocks emplaced on the Earth's surface, as opposed to within vents, have great potential to provide insight into eruptive dynamics, much as they have for other volcanic systems.

The IHV are located on the western side of the Archaean Tanzanian craton, several kilometres NW of the village of Igwisi. They were emplaced through granitic gneiss basement. The IHV were first recognised by the Geological Survey of Tanganyika in the early 1950s (Sampson 1953). Subsequent studies focussed mainly on the petrology of the lava flow from the NE volcano and its mantle xenoliths (Reid et al. 1975; Dawson 1994). Dawson (1994) concluded that the mineralogy, major element and isotope chemistry of the Igwisi Hills rocks have strong affinities with calcite-rich kimberlites (e.g. Benfontein sills, South Africa). Little is known about the physical volcanology of the volcanoes, except that they comprise three volcanic centres formed of cones and craters of pyroclastic rocks and lavas.

The IHV consist of three small volcanic centres (NE, Central and SW volcanoes) comprised of pyroclastic cones, craters and lavas. Together they constitute >3.2 × 10^6 m^3 of erupted products preserved above the Earth's surface and cover >2.7 × 10^5 m^2. The relative ages of the IHV cannot be fully constrained, although field relationships indicate that the Central volcano postdates the NE volcano. They are aligned NE–SW and sit upon a broad, low NE–SW-oriented ridge, 500 m wide that is probably comprised of pyroclastic material (poorly exposed) from early stages of the eruptions. The volcanoes have been partially buried by younger sedimentary rocks and soils, and are presently covered in grassland and low-density forest. They exhibit similar pyroclastic lithofacies and all have small volume extrusions of lava.

IGWISI HILLS VOLCANOES

NE VOLCANO

The NE volcano covers >1.9 × 10^5 m^2 and comprises a flat-bottomed sub-circular crater ~200 × 200 m in diameter surrounded by a partial low ring of outward-dipping pyroclastic rocks and by lava. Crater walls on the northern side comprise a succession of bedded and stratified pyroclastic rocks; its eastern side is comprised of lava. The northern and western crater walls are presently 4–8 m higher than the eastern crater wall. The south-western crater wall has been buried by lava from the Central volcano.

CENTRAL VOLCANO

The central volcano covers > 8.1 × 10^4 m^2 and is structurally simpler than the NE volcano (Fig. 1A). It has a minimum basal diameter of >300 m. The western side comprises a N–S oriented elongate partial cone of outward-dipping bedded pyroclastic rocks, in which beds dip towards the W, NW and SW. This pyroclastic mound rises 36 m above the surrounding plain and has outer slope gradients of ~24°. The eastern margin of the mound is an N–S oriented, near-vertical crater wall. We infer that the crater was open to the east—pyroclastic rocks do not outcrop on the eastern, northern or southern sides of the volcano. The crater currently sits beneath a lava coulée that makes up the eastern half of the volcano. To the west and north-west the Central volcano is surrounded by an apron of lithic-bearing coarse tuff (Fig. 1B).

Figure 1. Panoramic photographs of the three volcanoes. A) The NE volcano, showing the flat crater floor, the northern crater wall comprised of pyroclastic rocks, and the lavas on the eastern side. View looking north from the Central volcano. B) Central volcano showing the partial pyroclastic cone on the west of the volcano and the lava coulee that fills the inferred Central volcano crater and has partially filled the NE volcano's crater. View looking south from the northern margin of the NE volcano. C) The SW volcano showing the pyroclastic cone and central crater. The western side of the cone is 12 m higher than the eastern side. View towards the south from the Central volcano.

SW VOLCANO

The SW volcano is located 500 m southwest of the Central volcano (Fig. 1C). It comprises a sub-circular pyroclastic cone that covers >8.1 × 10^5 m^2, has a basal diameter of >300 m, and rises over 30 m above the surrounding ground. The north and west walls of the crater are 10 m higher than the south and east side and are breached to the northeast. The slopes of the cone dip ~17° on the west and north and 15° on the east and south. It has a 180 × 140 m diameter flat-bottomed crater perched 12 m above the surrounding ground.

PYROCLASTIC ROCKS

The oldest exposed pyroclastic rocks at each volcano are grey, massive to stratified lithic-bearing coarse tuffs (Fig. 2A). They are well exposed along the inner crater wall on the north of the NE volcano and in patchy outcrops on the ground on the northern exterior of the volcano. Similar tuffs were encountered in shallow trenches dug radially away from the Centre volcano. These tuffs reach 8 m thick although their base, and the pre-eruption substrate is not exposed and the apron is mostly covered by soil. The abundance of lithic clasts varies between 5–40 vol. %, with a typical abundance of 5–12 vol. %. There are two types of end-member pyroclasts in this lithofacies. The first are non-vesicular, crystalline and have irregular and amoeboid to subspherical shapes and are up to several millimetres in diameter. The second comprise lithic clasts, olivine crystals and olivine micro-xenoliths with an irregular coating of solidified kimberlite magma (pelletal clasts) similar to that which constitutes the first type of pyroclast. Coatings have uneven thicknesses around clasts and irregular morphologies.

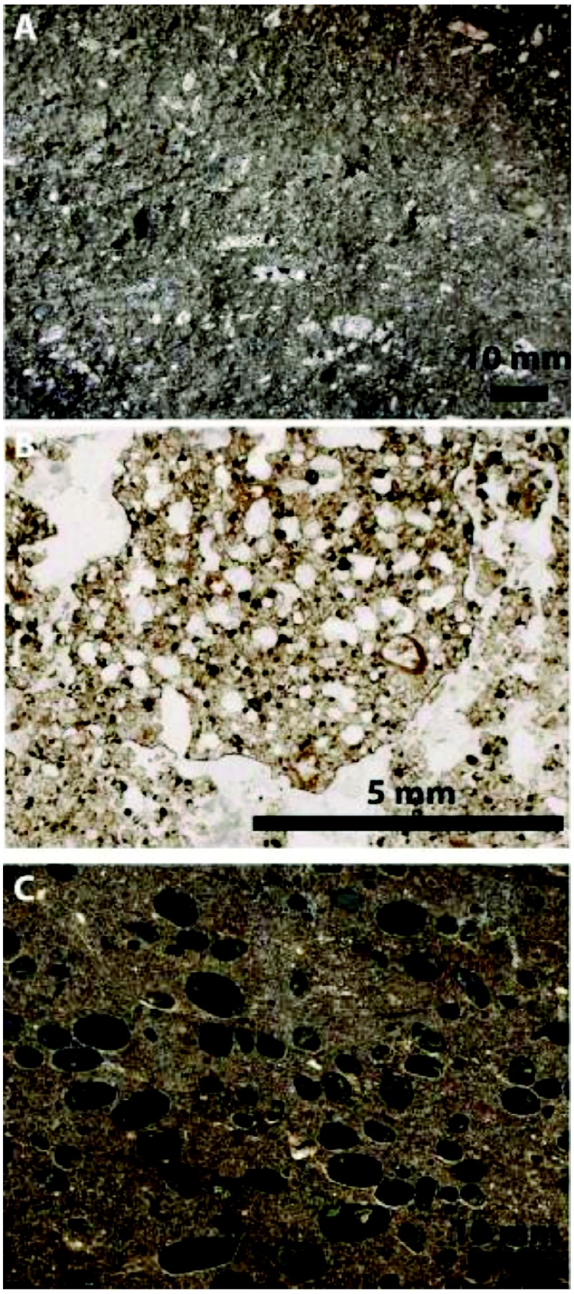

Figure 2. A) Close-up of lithic-bearing lapillistone with disseminated granitic clasts (NE volcano) **B)** Juvenile-rich lapillistone comprised of poorly vesicular lapilli and ash-grade juvenile clasts with irregular outlines (Central volcano). **C)** Olivine and olivine mico-xenoliths at base of lava flow from NE volcano.

The bulk of the pyroclastic rocks in the pyroclastic cones are comprised of bedded and stratified juvenile-rich tuff and lapillistone and pelletal clast-rich tuffs and lapillistones. Three types of pyroclasts occur within these juvenile rich lithofacies. The first are incipiently vesicular scoriaceous clasts up to coarse lapilli size (Fig. 2B). They have irregular, angular shapes. The edges of the scoria clasts cut through vesicles and there is no evidence for vesicle zoning or chilled exteriors. These have 10–20 vol. % subspherical, elongate to irregular-shaped vesicles 0.02–3 mm in diameter, some of which show evidence for coalescence. Vesicles have been partially filled with secondary calcite. The second are pelletal lapilli comprising olivine crystals and micro xenoliths which reach 10 mm in diameter. They are coated in a thin jacket of crystalline kimberlite magma, which is typically a few 10s of ìm thick, but in many cases only partially enclose the central grain. The third type is crystalline sub-spherical, dense crystalline juvenile lapilli < 1–300 mm in diameter.

LAVA

Lava flows are present at all three volcanoes. The best section through a lava is in the NE sector of the volcano to the east of a prominent notch in the crater walls. The lava exhibits both massive olivine-bearing lithofacies and vesicular lithofacies. It has a fine-grained crystal-poor base and a very crystal-rich olivine normal-graded lower third (Fig. 2C). Large olivine crystals vary in abundance up through the lava, but generally decrease in abundance upwards (from 26 vol. % to 5 vol. %), above the thin olivine-poor base. Note that many of the large olivine crystals are multigrain aggregates and can be regarded as micro-xenoliths (Dawson 1994). The upper parts of the lava are poorly to moderately Vesicular (<15 vol. %). Vesicles vary from 1–40 mm in diameter, are sub-spherical to irregular in shape and some are sheared and coalesced (Fig. 6). Most vesicles are lined with a thin coating of carbonate. Layering within the lava dips 28° SSE. The lobate margin of the NE volcano lava flow has been defined by scattered outcrops on the forest floor and by the position of loose lava blocks and boulders. In total, lava from the NE volcano covers >1.5 × 10^5 km^2 (including lava in the crater) and assuming an average thickness of 2.5 m it has a minimum volume of >3.7 × 10^5 m^3. The flat-lying lava flow covers 8 × 10^4 m^2 and assuming a similar average thickness has a volume of ~2 × 10^5 m^3.

A lava coulée sits in the crater of the Central volcano. The lava is dense, homogeneous, reddish-brown, and contains scattered basement inclusions. It is 150 m wide, rises 40 m above the crater floor of the NE volcano and extends >250 m towards the southwest to cover an area of > 3.4 × 10^4 m^2. It has a minimum volume of 4 × 10^5 m^3 (calculated above ground level). The overall appearance is of two bounding levees with a slightly lower central channel to the SE. To the west, it abuts against the crater wall of the pyroclastic cone. Its southwest margin is inferred from the position of large blocks of lava and scattered outcrops on the forest floor that define a broad, lobate terminus, 180 m wide. The northern and eastern exteriors of the coulée are steep (29–32°) and are partially covered by soil and talus rocks, while the south-west exterior dips 2–3°. Rounded olivine xenocrysts >5 mm account for >2 vol. % of the rock. It has a fine- to medium-grained serpentine-calcite-apatite-spinel-perovskite groundmass. Basement clasts are commonly recess-weathered and range in diameter from <0.1–8 cm in diameter. They are typically rounded and are granitic or dioritic in composition. They are irregularly scattered throughout the coulée and reach 2.5–5.5 vol. %. Parallel, curving and cross-cutting centimetre-spaced joint sets are present within the rock.

COSMOGENIC THE DATING RESULTS

Three samples were taken for cosmogenic He exposure dating. One sample (IH15) was taken

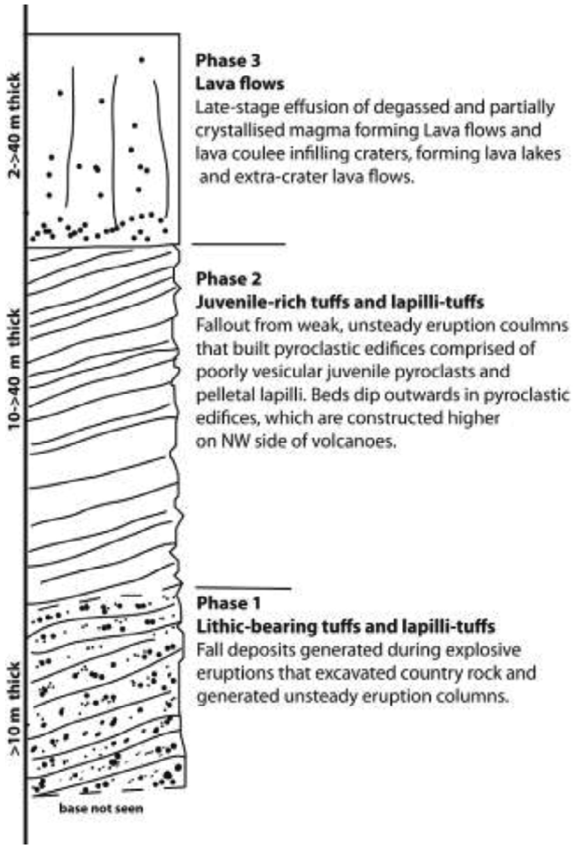

Figure 3. Graphic summary log showing the deposits of the three main eruption phases that characterised the IVH eruptions.

from the eastern summit of the lava coulée of the Central volcano under very sparse woodland. Two samples (IH52 and IH61) were taken from the NE volcano. Sample IH61 was collected from the weathered upper parts of the lava flow under sparse woodland. Sample IH52 is from a scarp cut through the interior of the lava along the eastern crater wall. Samples IH15 and 61 were considered to be close to the original surface of the lava flows (<1 m). Sample IH52 represents an exposed footwall generated during late-stage subsidence in the NE crater. Sparse vegetation cover (trees and bushes) is present at all samples sites but has not been sufficient to require correction, and no depth correction or self-shielding corrections were necessary. Topographic shielding is significant (~30%) for sample IH52.

Exposure ages range from 5.9–12.4 ka. The low concentration of cosmogenic ^3He has resulted in relatively large age uncertainties, in one case up to 70 %. The arithmetic mean of the exposure ages suggest that the Igwisi Hills volcanoes were erupted at 8.9 ± 2.7 ka (1s, n = 4). However, IH15 and IH61 have probably experienced a small degree of erosion, which suggests that the slightly older ages determined for sample IH52 (11.2 ± 7.8 and 12.4 ± 4.8 ka) are better estimates of the eruption age.

INTERPRETATION

The IVH provide insights into how kimberlite magma may behave at the Earth's surface that have not been possible through study of kimberlite pipes. Each volcano broadly shows the same three eruptive phases (Fig. 3): 1) early vent-clearing explosive eruptions comprising elevated quantities of fragmented country rock; 2) lower-intensity juvenile-rich explosive eruptions that generated weak eruption columns that were strongly sheared by dominant winds from the east and south-east, and that constructed pyroclastic edifices around the vents and; 3) waning-stage effusions of degassed and partially crystallised viscous lava. The IVH are small volcanoes in comparison to many well-studied kimberlite pipes. The total volume of preserved explosive and effusive products at each volcano ranges from 9×10^5–1.3×10^6 m^3. The volumes of erupted material dispersed widely by ash clouds during the eruptions and removed from the volcanoes by erosion are not known. The dimensions of the conduits and the volume of juvenile material contained within them also remain largely unconstrained. Surface crater radii of 50–100 m. constrain the maximum diameters of the conduits, but the vertical extent and shape of the conduits (i.e., whether they are typical carrot-shaped kimberlite pipes or not) is unknown. In ancient kimberlites pipes and other diatremes within hard crystalline host rock, pipe walls are typically oriented inward at angles of 70–90°, with average dips of 82–85° inferred for kimberlite pipes (Hawthorne 1975). Using these average values, kimberlite pipes beneath the Central and SW volcanoes may extend 300–500 m below the surface, while that situated beneath the NE volcano could reach 600–900 m below the surface (Fig. 12). Deep craters also help explain the lack of ballistic ejecta with confinement of relatively weak explosive activity deep within the vent.

A conservative estimate would put the volume of erupted material trapped within each IHV conduit at 10^5–10^6 m^3. Accounting for eroded and subsurface material would mean that the IHV eruptions were at least VEI 2 in magnitude (>0.01 km^3). This is at the lower end of estimated volumes for kimberlite eruptions (Sparks et al. 2006) and is consistent with their small crater diameters. We conclude that the IHV were formed by small volume, monogenetic eruptions that probably each persisted for several days up to several months (comparable in duration to monogenetic basaltic eruptions). The eruptions were probably similar to those that formed small melilitic and nephelinitic volcanoes in northern Tanzania (see Dawson 1964; Mattsson and Tripoli 2011). Such young eruption ages may indicate that the Tanzanian craton is undergoing a new phase of kimberlite volcanism and more eruptions of kimberlite magma may be expected in the future.

CONCLUSIONS

The three Igwisi Hills volcanoes, Tanzania, are the only examples of kimberlite volcanoes that still have surface constructs preserved at the Earth's surface. Cosmogenic ^3He exposure dating of olivine in the lavas gives Upper Pleistocene/ Holocene eruption ages. This age is confirmed by palaeomagnetic analyses and confirms them as the youngest known kimberlite bodies. The three small volcanoes comprise pyroclastic edifices, craters and lavas and were generated by small-volume (VEI 2), monogenetic eruptions of kimberlite magma that reached the Earth's surface along a NE–SW-oriented dike or dikes. The pyroclastic cones are comprised of diffusely bedded fall deposits and pyroclasts include vesicular scoriaceous clasts, pelletal clasts and dense juvenile clasts. Bedding and pyroclast characteristics are consistent with repetitive small explosions that may be dynamically similar to Strombolian eruptions. Pyroclasts are similar in size and morphology to those commonly found in other kimberlite rocks (in kimberlite pipes) indicating overlap in magma fragmentation dynamics between the Igwisi eruptions and those recorded by ancient kimberlite pipes. The eruption pathways of the IHV are comparable to those observed at and inferred for eruptions of other types of magma.

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