VOLCANIC GEOLOGY OF MOUNT SUSWA, KENYA

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[Plates 4 to 9; pull out map in colour]

CONTENTS

Mount Suswa is a low-lying Quaternary volcano in the Eastern Rift Valley of Kenya. It rises from the south-sloping floor of the Rift as an asymmetric, shield-shaped cone that covers an area of about 270 km^2. The volcano consists of sodalite-bearing, phonolitic lava flows and subordinate proportions of pyroclastic rocks. The cone was built on a volcanic plateau composed of quartz-bearing, trachyte flood lavas (Plateau Trachyte Series; Baker 1958).

The volcanic history of Mount Suswa can be divided into three major eruptive episodes: (1) formation of a primitive, shield-shaped volcano composed mainly of lava flows derived from central sources; (2) eruptions at the time of cauldron subsidence producing abundant pumice and thick lava flows, most of which issued from a ring-fracture zone outside, and concentric with, the caldera escarpment ('ring-feeder' lavas); (3) post-caldera lavas which partly filled the caldera and later built Ol Doinyo Nyukie volcano. Towards the end of the last eruptive episode an unusual collapse feature, in the form of a 'ring graben', was formed inside the older caldera.

South of Mount Suswa a series of north–south linear faults transect the plateau basement of trachyte flood lavas. Near the southern periphery of Mount Suswa these faults die out, in some cases converging toward the centre of the volcano. Also in the south it is not always possible to distinguish between the quartz-bearing, trachyte flood lavas of the Rift floor and the sodalite-bearing flows from the central vents of Mount Suswa. (Sodalite-bearing flood lavas are known to be present.)

The primitive volcano consists of lava flows, the earliest of which are the most voluminous. An unusual heterogeneous rock comprises the upper parts of the youngest primitive volcano flows. The rock consists principally of globules of lava moulded on to each other, each with a continuous glassy rim and a vesicular, crystalline core. The flows have been termed 'globule-surface lavas' (Johnson 1968). Other heterogeneous glassy rocks on Mount Suswa resemble examples from the controversial 'froth flows' described from various parts of Kenya (including Mount Suswa) by McCall (1965) and McCall & Bristow (1965).

After a period of quiescence, a caldera was formed in the summit of the primitive volcano. The relationships between the caldera escarpment and the pumice and ring-feeder lavas on Mount Suswa are described in detail. These relationships are significant because they question the widely held assumption that, in calderas with thick pumice mantles, it is the rapid expulsion of pumice (producing a void in the magma chamber) that leads to the collapse of the magma chamber roof. This process, known widely as the 'Krakataun' mechanism (Williams 1941; after van Bemmelen 1929), is not applicable to Mount Suswa since the pumice and ring-feeder lavas mantle the caldera escarpment. Instead, as previously suggested by McCall (1963), a more likely process is that releases of pressure along the ring faults, formed during cauldron collapse, produce the explosive eruptions. In reviewing and discussing in detail the literature on calderas, it is concluded that many so-called 'Krakatau-type' calderas may

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have originated in the same way as the Mount Suswa caldera. Furthermore, it is emphasized that in the case of any one caldera great care must be taken in describing and interpreting the often ambiguous relations between cauldron subsidence and concomitant explosive eruptions.

The post-caldera sequence of lavas on Mount Suswa is divided into two parts: an earlier group of generally non-porphyritic lavas; and a later group of distinctive, porphyritic lavas containing abundant anorthoclase phenocrysts. Most of the flows of the later group were erupted from a central vent in the southwest part of the caldera. They produced Ol Doinyo Nyukie volcano, at the summit of which is a pit crater.

The second major collapse on Mount Suswa took place entirely within the older caldera and produced an annular trench, or 'ring graben'. This unusual structure consists of two, more or less concentric, fault scarps bounding a steep-sided annular zone of subsidence. The ring graben truncates the pit crater of Ol Doinyo Nyukie and isolates a tilted, flat-topped, central island-block with a maximum diameter of 3.75 km. The island-block is inaccessible and its detailed structure is unknown. Consequently, the origin of the ring graben is still uncertain. However, three possible subsidence mechanisms are suggested.

A fresh lava flow, similar to those of Ol Doinyo Nyukie volcano, partly covers the floor of the ring graben. This flow, and a similar one on the south flank of Mount Suswa, are the most recent eruptions of the volcano. Fumarolic activity persists at the present day.

1. INTRODUCTION

Sodalite-bearing phonolitic lava flows and pyroclastic rocks constitute the low-lying Quaternary volcano of Mount Suswa in the Eastern Rift Valley of Kenya. This account of the eruptive history of Mount Suswa is based on a Ph.D. thesis submitted to the University of London (Johnson 1966*a*).

(*a*) *Geological setting*

Mount Suswa is shown in figure 2 in relation to the Eastern Rift Valley and other volcanoes of the East African volcanic field. The Rift Valley lies along the north–south axis of a regional upwarp which Baker (1965) described as 'an oval area of high-land centred on Nakuru...an area of up-warping which was uplifted repeatedly in Caenozoic times'. Mount Suswa lies on the southern flank of this rise, about 110 km south of Nakuru and 45 km west of Nairobi.

Mount Suswa is one of a series of Quaternary volcanoes on the Rift Valley floor. These include Longonot, Menengai, Kilombe and Silali, all of which, like Mount Suswa, show calderas in primitive cones composed mainly of phonolite and trachyte lavas.

(*b*) *Topography*

Mount Suswa is one of the largest and most complex of the Quaternary volcanoes in the Rift Valley. Its products extend across almost the whole width of the valley floor, and probably cover a total area of the order of 1000 km^2. It forms an asymmetric, low-lying, shield-shaped cone, rising from the floor of the Rift, at 1525 to 1615 m above sea-level, to a maximum altitude of 2357 m at Ol Doinyo Nyukie trignometric point. The asymmetry of the volcano is due mainly to the southerly dip of the Rift Valley floor. This is best illustrated on the geological map (figure 16, facing p. 406) by lavas on the eastern flank of Mount Suswa which turned south as they flowed away from the volcano and down the sloping plateau.

Rock exposure is good on higher parts of the mountain but on lower slopes alluvial cover is thick and extensive; dry scrub and grass covers much of the volcano at all altitudes. Dissection is mainly in the form of narrow gullies, many of which are controlled by the edges of lava flows. There are no running streams on the mountain and the only sources of rain water are temporary shallow pools that form after infrequent storms. Masai tribesmen are the only human inhabitants.

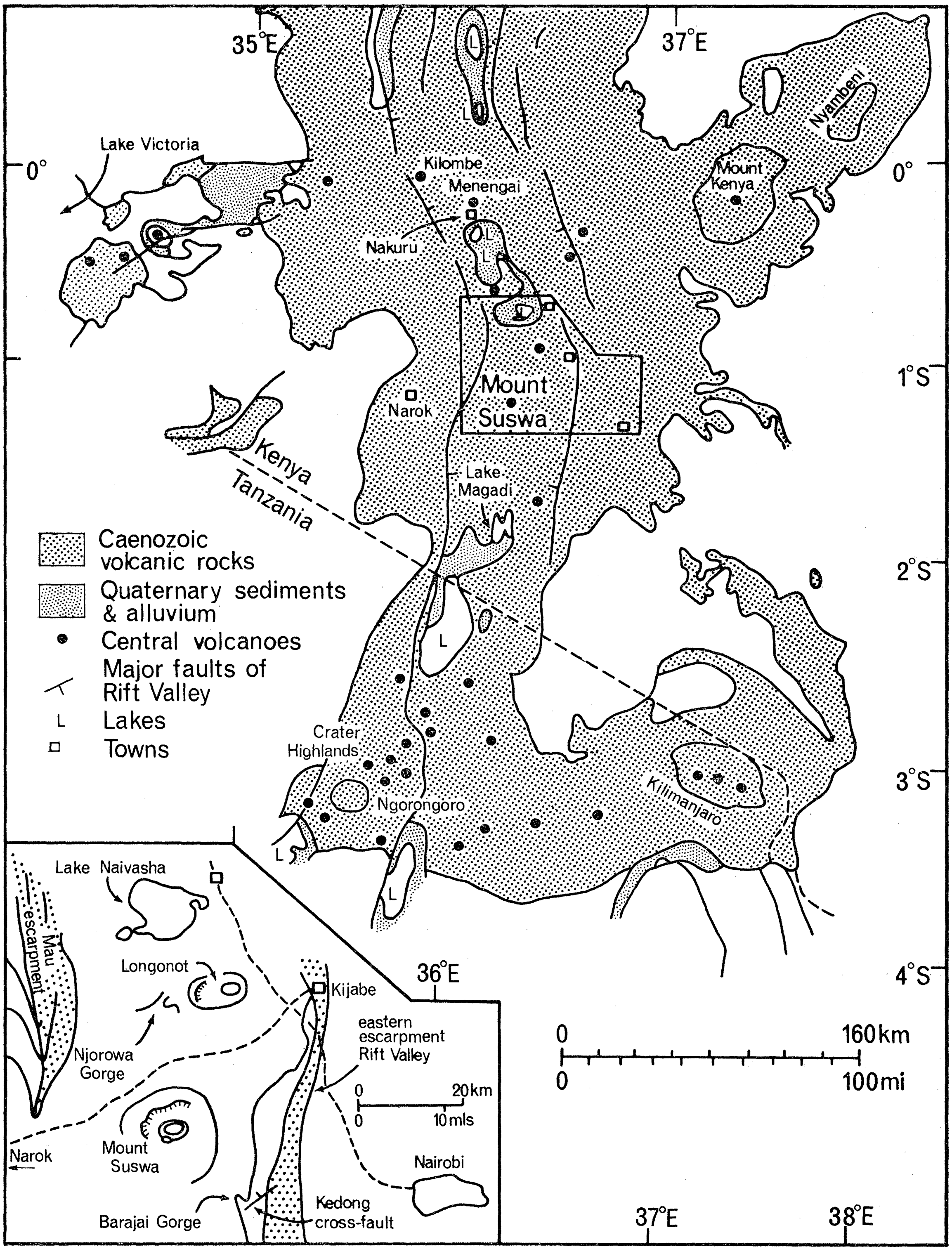

Figure 2. Index map of Mount Suswa and East African Caenozoic volcanic field.

Access by motor to the summit of the mountain is possible by leaving the Narok–Kijabe road 13 km west of its intersection with the Nairobi–Nakuru highway, and using a rough temporary track ascending the northeast outer flank.

(*c*) *Previous work*

None of the early references to Mount Suswa contributes significant information on the geology, and it was not until 1960, when an extensive network of lava tubes was discovered on the eastern slopes, that geological investigations were undertaken. McCall & Bristow (1965) gave an introductory account of the geology, and Williams (1963) and Glover, Glover, Trump & Wateridge (1964) described the lava tubes. McCall & Bristow's account described in general terms the history of the volcano, the structure of the unusual caldera and 'ring graben', and the petrography of a limited suite of specimens. A sketch map drawn from air photographs was also presented.

2. GENERAL STATEMENT

The Mount Suswa sequence may be divided into three major eruptive episodes each of which produced phonolitic lava flows and pyroclastic rocks (figure 3). Chemically, the flows contrast with quartz-bearing, alkali trachyte, flood lavas that constitute the plateau basement of the volcano.

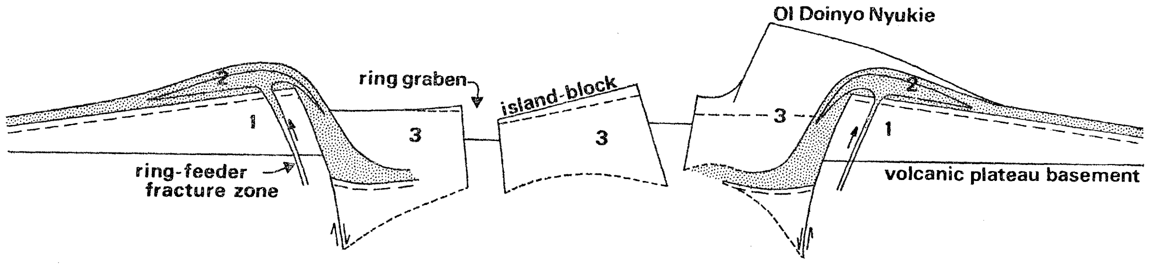

FIGURE 3. Three major eruptive episodes of Mount Suswa in schematic cross-section. (1) Primitive shield volcano; (2) ring-feeder lavas and pumice (stippled); (3) post-caldera lavas, later flows constituting Ol Doinyo Nyukie volcano. The diagram illustrates a north-south section in which the caldera is about 9 km wide and the summit of Ol Doinyo Nyukie is approximately 750 m above the volcanic plateau basement.

The first eruptive episode produced a primitive, shield-shaped volcano consisting mainly of lava flows. The second episode accompanied the formation of a caldera in the summit of the early cone and gave rise to thick pumice deposits and 'ring-feeder' lavas that originated from a ring fracture zone outside, and concentric with, the caldera escarpment. The third episode produced lava flows which partly filled the caldera. Subsequently, highly porphyritic, post-caldera lavas built the well-defined cone of Ol Doinyo Nyukie ('The Red Mountain') at the summit of which is a pit crater.

A second, major collapse structure on the north flank of Ol Doinyo Nyukie, and inside the older caldera, has the form of an annular trench or 'ring graben' that isolates a tilted, central 'island-block'. The floor of the ring graben is partly covered by a porphyritic lava similar to a second flow—of presumed post-ring graben age—on the south flank of Mount Suswa.

Fumarolic activity persists at the present day.

There is little variation in the mineral-content of the Mount Suswa lavas throughout the succession. Variable proportions of phenocrysts include, in order of abundance, soda-rich

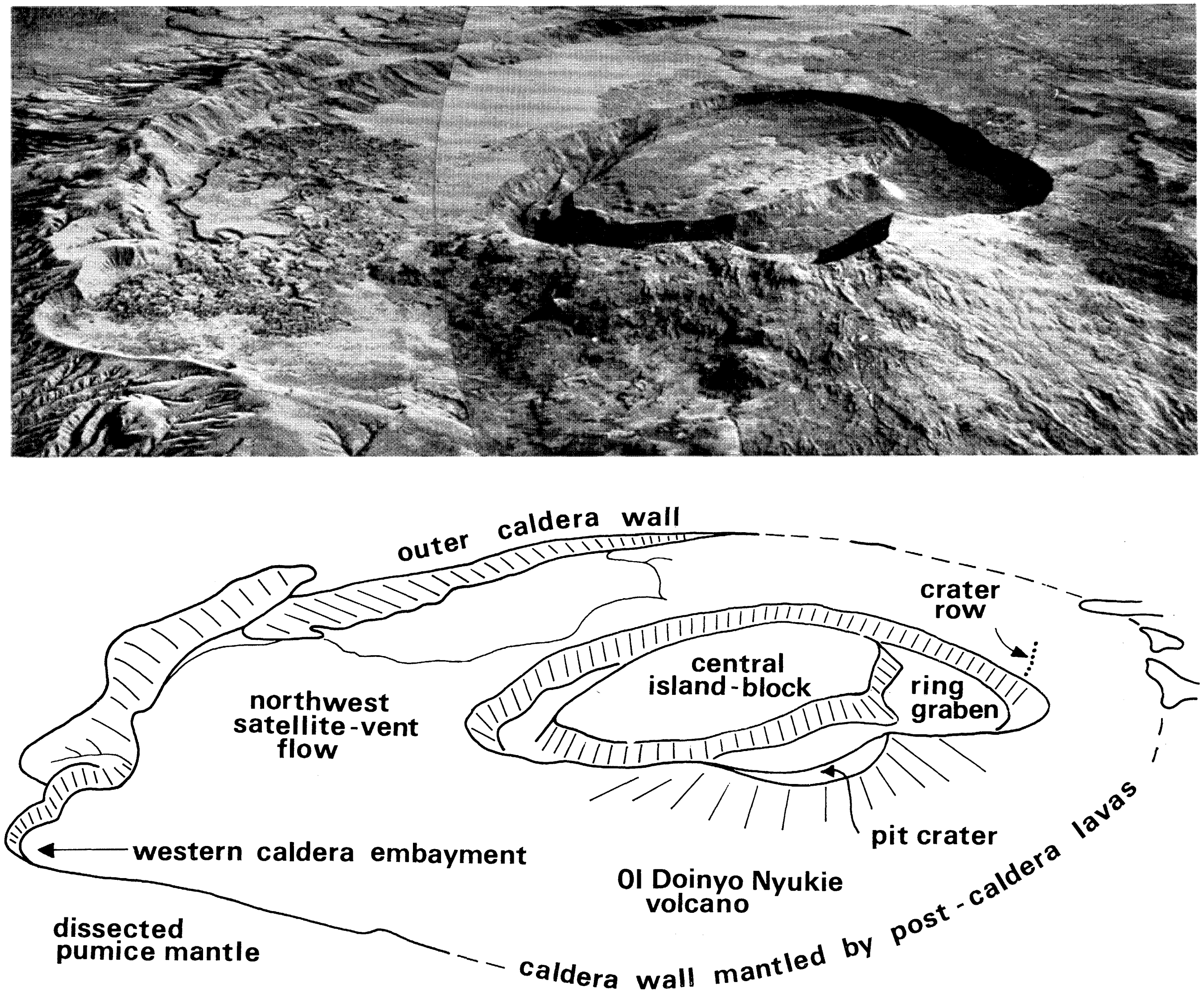

FIGURE 1. Aerial photograph of Mount Suswa caldera and ring graben taken from the southwest; from original photographs by T. A. Tomalin, supplied by P. E. Glover, Nairobi.

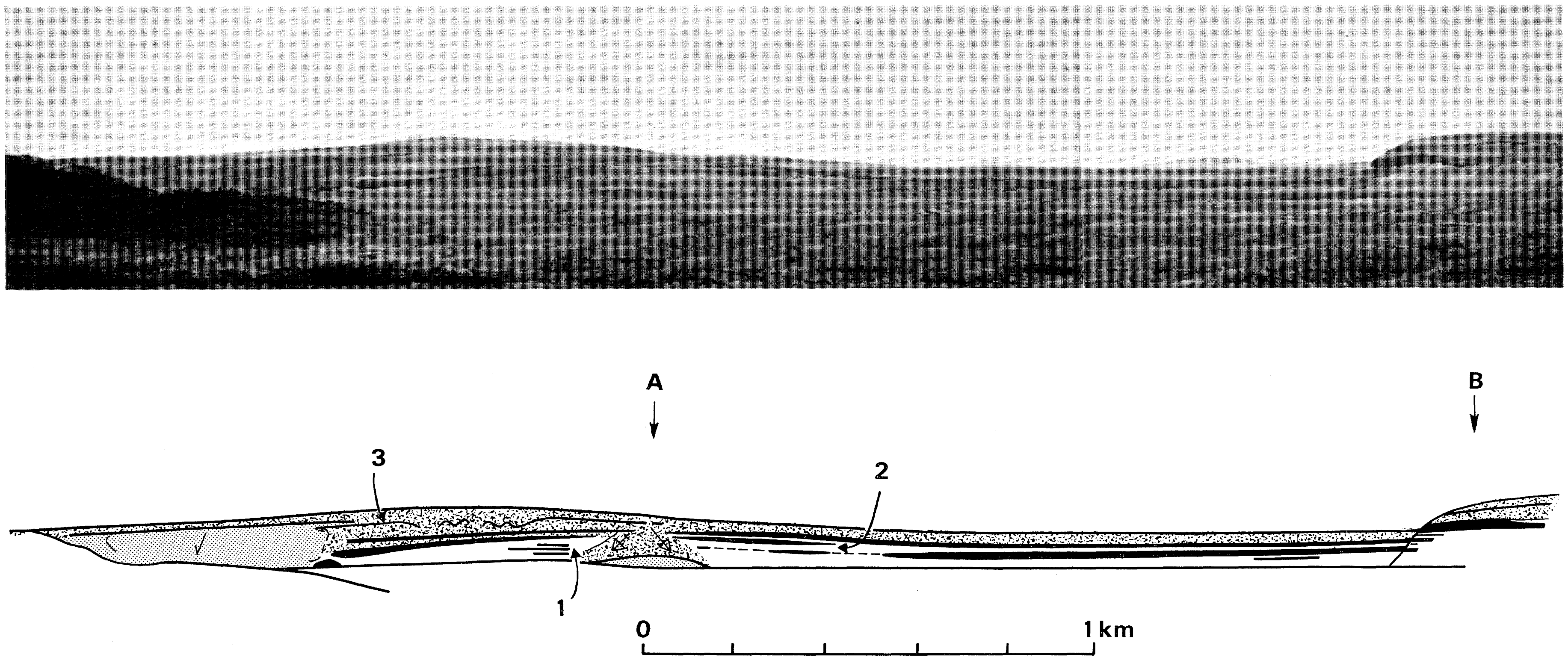

Figure 7. Embayment in the western caldera wall. Left of A and right of B, ring-feeder lavas dip into the caldera. Between A and B, they dip outwards to the west. The thick extensive flows shown in solid black thin towards. A The lower of the three, thin, poorly exposed flows at 1 is possibly a primitive volcano lava. Sediment-filled scourings are present beneath the flow labelled 2 (erosion surface E3 of figure 13). The pumice mantle of the western flank occupies the upper part of the section. 3 is a conspicuous, inward-dipping spatter bed intercalated with the pumice. The 7 m thick, finely bedded unit (not shown on this diagram for clarity; see figure 6) caps the section right of A. Left of A, it is overlaid by thicker beds of coarser pumice and is traceable, without break, to the extreme left. Photographs by T. Reilly.

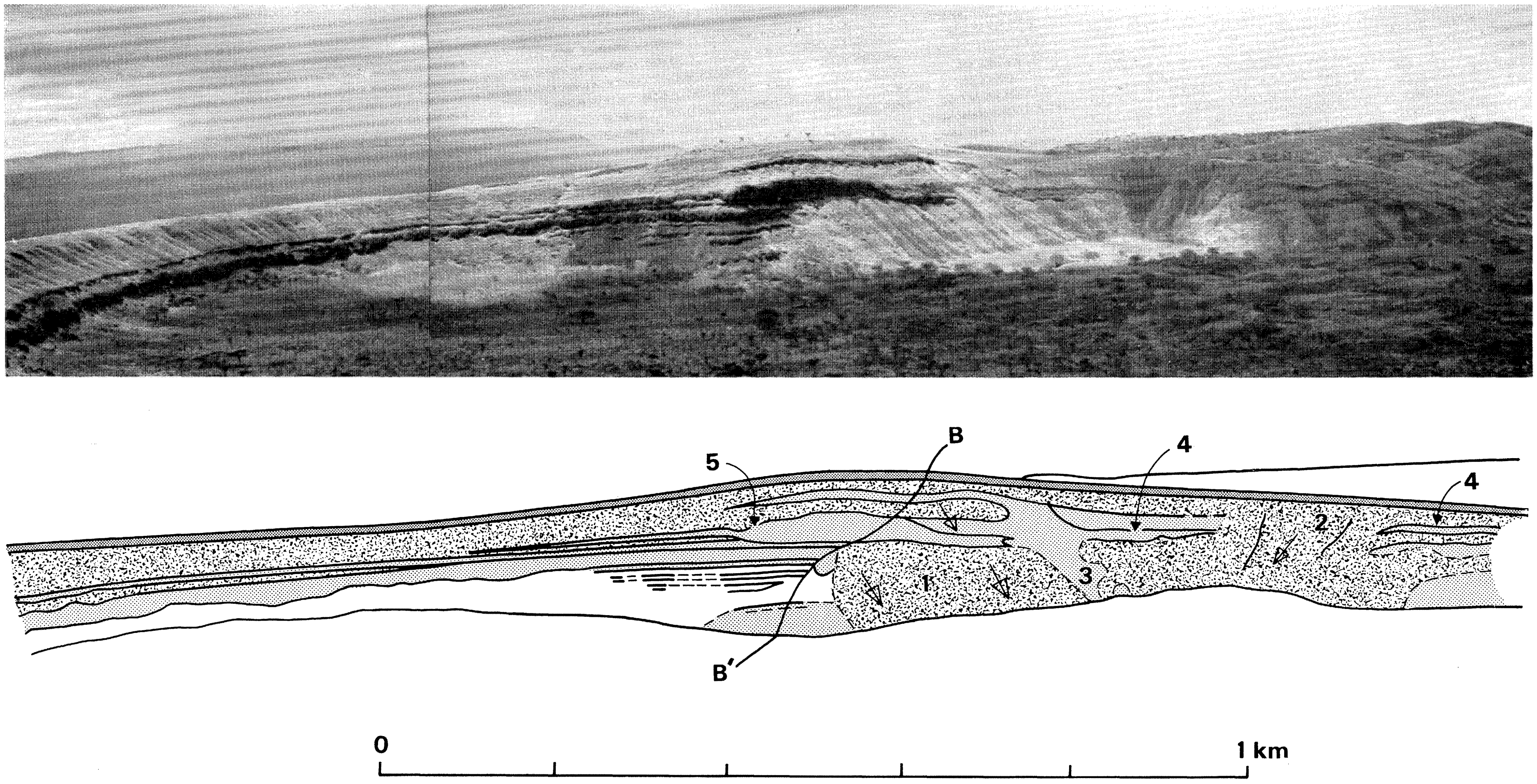

FIGURE 8. Western caldera wall. Line BB′ marks the inferred trace of the ring-feeder fracture on the caldera wall. Left of BB′ (inside the embayment), ring-feeder flows and pyroclastic beds dip outwards to the northwest. Right of BB′, lavas dip into the caldera, and pumice beds are inclined against the caldera escarpment (1), in one place completely mantling it (2). The lavas show a variety of forms: thin ‘flows’—probably spatter beds—uniformly cover the pumice banking (3); thicker flows show truncated portions formed by collapse due to viscous flow down steep inclines (4). Left of BB′, truncation of the thick lenticular flow (5) is due to collapse of the embayment. Right of BB′, the initial form of the scarp was probably due to collapse during viscous inward flow, with later modification by erosion. Photographs by T. Reilly.

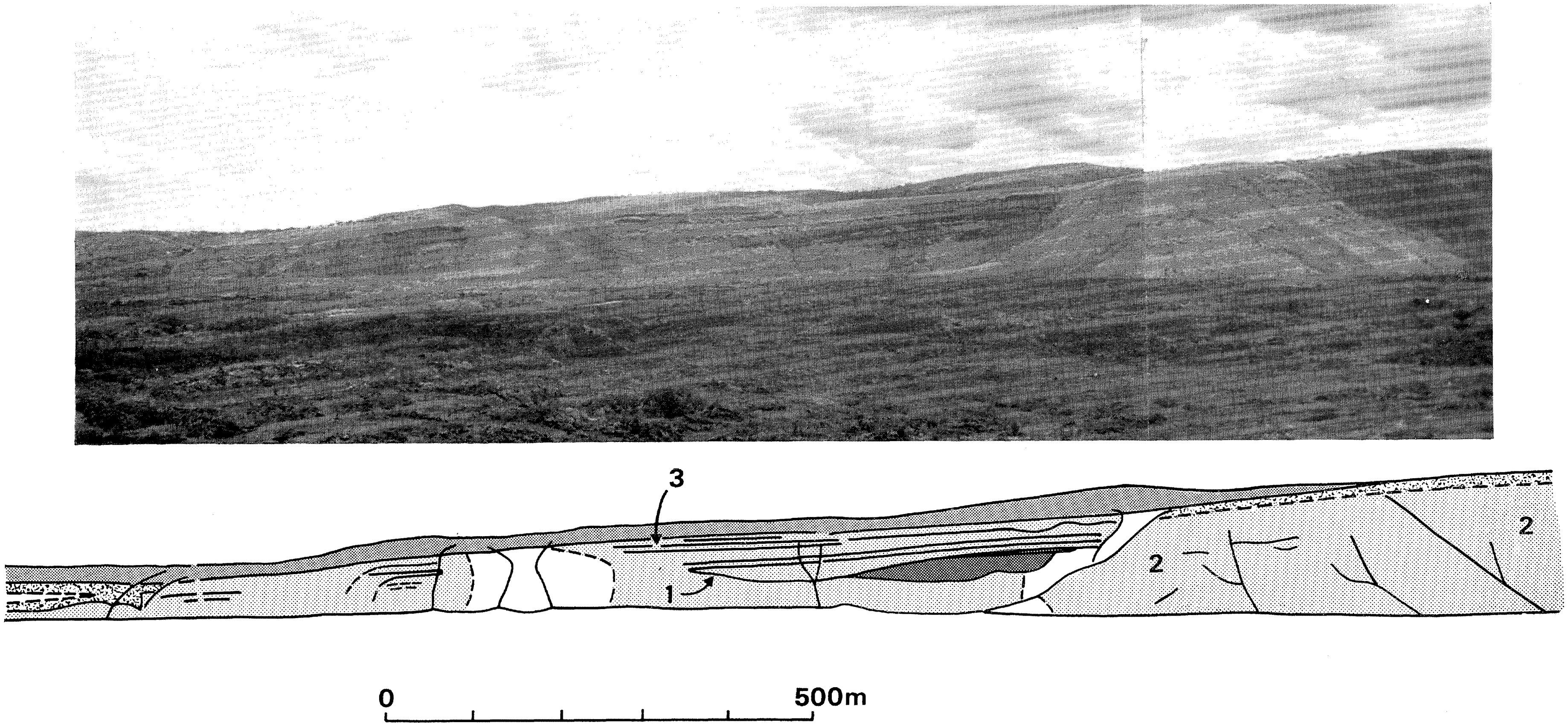

Figure 9. Northwest caldera wall, showing complex of inward-dipping ring-feeder lavas, spatter beds, and bedded pumice, all of which mantle the caldera escarpment (much of the detail on this section is omitted for clarity). The thickest ring-feeder flow (1) dips into the caldera and overlaps two earlier flows which probably belong to the primitive volcano. At the extreme right (2), ring-feeder lavas completely cover the caldera escarpment. In contrast, many of the ring-feeder flows to the left of 2 are truncated, probably due to viscous inward flow down the steep escarpment with later modification by erosion (3). The finely-bedded unit mantles the summit of the escarpment; it dips into stream channels, reflecting the dissected surface on which the ash was deposited (erosion surface E2 of figure 13). The post-caldera, northwest satellite-vent flow is shown in the foreground. Photographs by T. Reilly.

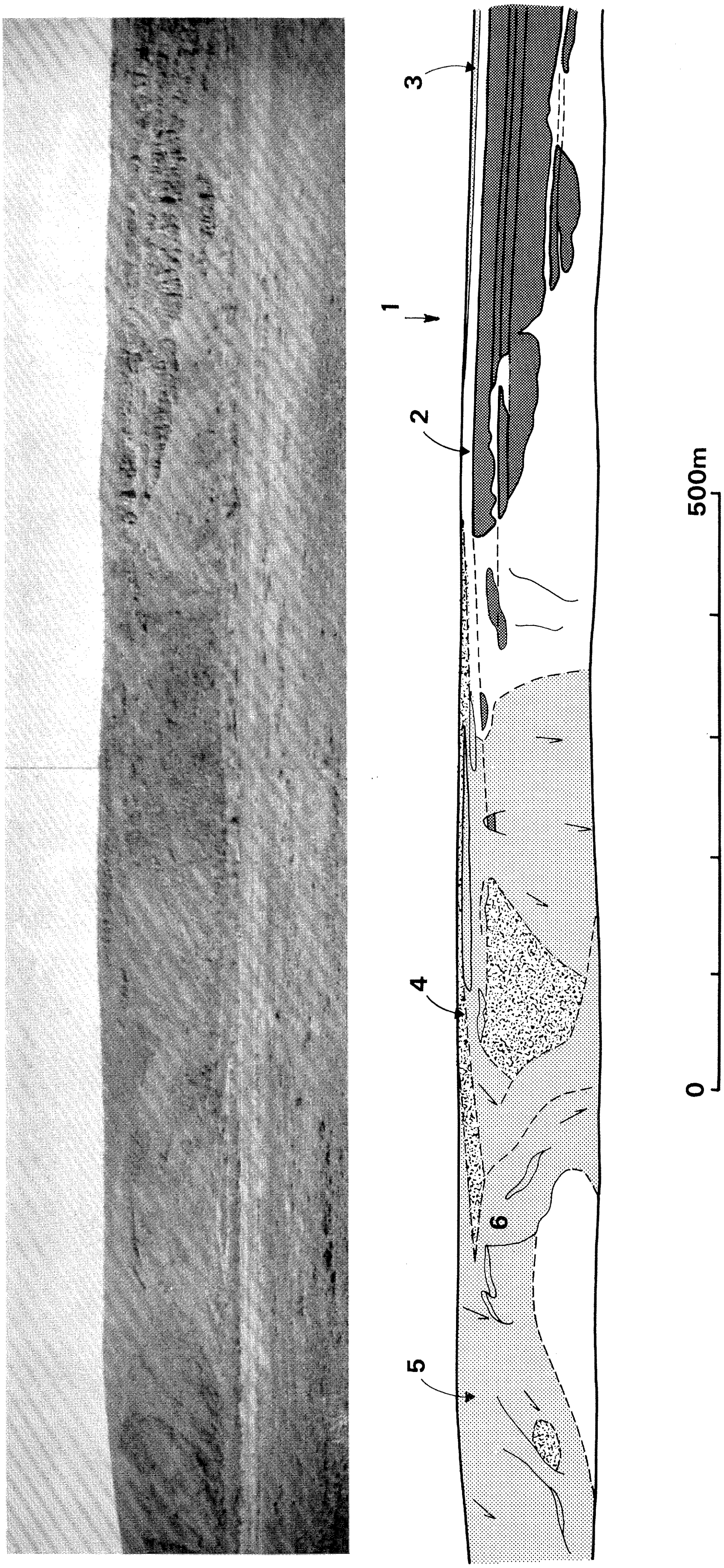

Figure 10. Northeast caldera wall, showing six, near-horizontal, primitive volcano flows (flow thicknesses given in text measured at 1), overlaid by deposits of early pyroclastic eruptions (2; bedded ash and accretionary lapilli). Ring-feeder flow at 3 (also see figure 11) thins out to the left where it is replaced by mantling pumice beds (4). At 5, ring-feeder lava completely covers the escarpment, showing flow scarps on the higher parts of the caldera wall (6).

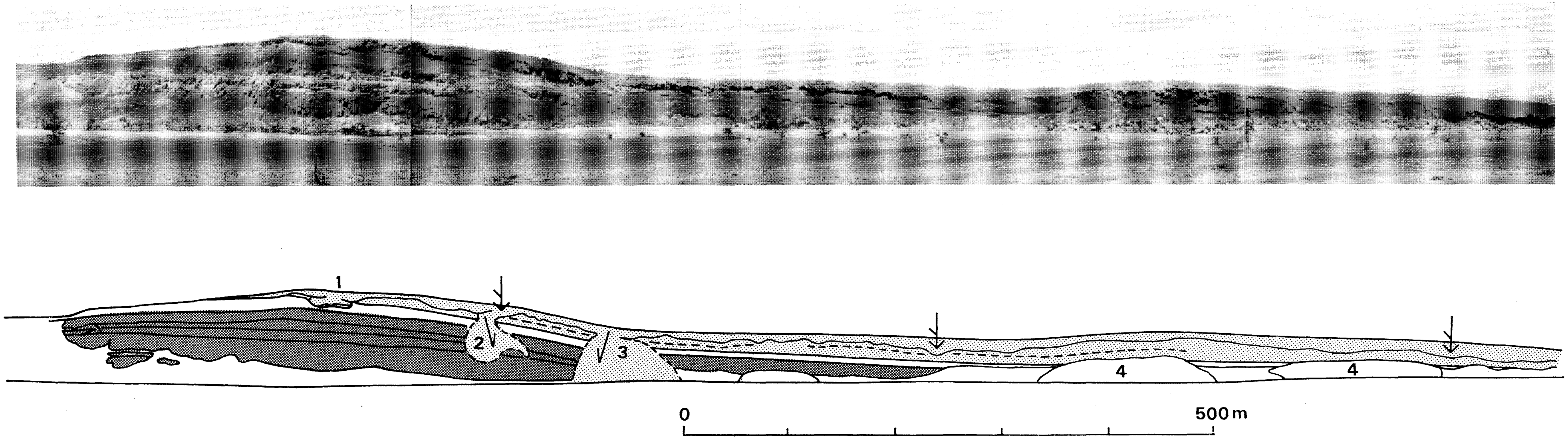

Figure 11. Northeast caldera wall, showing six primitive volcano flows, overlaid by deposits of early pyroclastic eruptions (and a thin layer of coarse pumice). The six flows show no visible intercalated pyroclastic horizons, prominent erosion surfaces, or 'globule-surfaces'. The upper ring-feeder flow has a near-horizontal base, but its upper surface is cambered, with a northerly dip on to the outer flank and a southerly dip into the caldera. Below the dashed line, the ring-feeder lava is massive and columnar-jointed. Above the line, the lava is more cavernous, shows no jointing and, because of greater fluidity at the time of eruption, extends farther down the fault scarp, giving irregular lobes (1), and partial (2) and complete (3) mantling of the primitive volcano lavas. At (4), talus blocks of ring-feeder lava have accumulated.

alkali feldspar, augite, fayalitic olivine, titanomagnetite and, to some extent, sodalite and nepheline. The matrixes of the lavas vary from glass containing alkali feldspar laths, opaque grains and sparse nepheline crystals, to a completely crystalline groundmass in which sodalite, augite, aenigmatite and soda-amphibole are present as additional constituents. Many of the glassy rocks are heterogeneous with patches, lenses and lamellae of more crystalline, and generally more vesicular material in a darker, glassy matrix. These rocks are similar to some described by McCall (1965) from the controversial 'froth flows' found in various parts of the Rift Valley.

The eruptive history of the volcano is described in the following five sections. In § 8, special attention is paid to the origin of the Mount Suswa caldera and of calderas in general. The petrology of the Mount Suswa phonolites is to be presented in a separate publication (Nash, Carmichael & Johnson, in press).

3. Volcanic plateau basement

Two groups of flood lavas constitute the flat-lying, plateau basement on which Mount Suswa was built (figure 16). In both groups, flows were emplaced by lateral flooding from sources which may have been single, central vents but were probably linear fissures.

The younger, more voluminous group consists of trachyte lavas that are well-exposed in subvertical escarpments of a series of north–south linear faults which repeatedly transect the terrain south and southeast of the mountain. These lavas accord with field and petrographic descriptions given by Baker (1958, 1963) for Lower Pleistocene 'Plateau Trachyte Series' lavas of the Lake Magadi region, an area 80 km south of Mount Suswa which is similarly affected by the distinctive 'grid faulting' (Gregory 1921). Representatives of the Series at the periphery of Mount Suswa therefore mark the northern end of a belt of plateau lavas that extends southwards, without break, for 120 km to the Kenya–Tanzania border (figure 2).

The Plateau Trachyte Series lavas are fine-grained, brownish to greenish grey in colour and contain a few alkali feldspar phenocrysts. Flow thicknesses vary from 2 or 3 m to over 40 m, and lavas retain their uniformity of texture and thickness for many kilometres along strike. In any one section up to three or four successive flows may be seen. The Plateau Trachyte Series and Mount Suswa lavas are similar in hand specimen, but are distinguishable under the microscope since the flood trachytes contain no feldspathoids, and a few of them carry interstitial quartz (Baker 1958). Other distinguishing petrographic features of the plateau trachytes are smaller quantities of interstitial ferromagnesian minerals and a distinctive soda-amphibole.

In figure 16 Plateau Trachyte Series flows are shown as one group; however, specimens from a number of thin, flood lavas, south of the volcano, contain sodalite. Sodalite is the characteristic mineral of the Mount Suswa lavas, but is not reported by Baker from the Magadi region. These thin, undersaturated flood lavas, therefore, probably represent local effusions of phonolite at sites later covered by lavas derived from the central vents of Mount Suswa. In the absence of distinctive field characteristics, however, the extent of the undersaturated flood lavas remains uncertain.

The older group of flood lavas are weathered, highly porphyritic trachytes that constitute isolated areas of terrain near Mount Suswa. In the central sector, immediately south of the volcano, the flows are displayed in small, isolated, horst blocks around which poured lavas of the later Plateau Trachyte Series (figure 16). To the southeast, the older porphyritic flows are prominent in larger and wider horst ridges, and in the Kedong fault scarp, trending N 55° E towards the eastern escarpment of the Rift Valley (figure 2). The flows are characterized by abundant alkali feldspar phenocrysts, often in glomeroporphyritic aggregates, set in a matrix similar to that of the Plateau Trachyte Series lavas; augite and fayalite microphenocrysts are also present. Neilson (1921) described an 'anorthoclase–phonolitic–trachyte' (specimen number 193) which was collected by Gregory (1921) from the Kedong cross-fault scarp. This rock was later termed 'soda-trachyte (Gibele type)' by Campbell Smith (1931).

Eruption of both groups of flood lavas took place during episodes of block faulting. In the Magadi area, Baker (1958) concluded from palaeontological evidence in the Olorgesailie lake beds that grid-faults are 'entirely lower Middle Pleistocene in age', only 'minor faulting' having taken place during the Upper Pleistocene. Evidence from the Mount Suswa area suggests that faulting was intermittent during the early Pleistocene. Early movements took place along cross-fractures of ENE–WSW trend, as well as along prominent north–south faults, producing elongate horst blocks. Later Plateau Trachyte Series lavas that flowed around the fault blocks were truncated by renewed movements, mainly along the same north–south faults bounding the horsts on their west and east sides. Even younger Mount Suswa lavas that flowed over the same grid-faults were also affected by subsequent displacements. These observations agree with the statement of Shackleton (1948) that 'movements took place intermittently but apparently always in the same sense at any particular fault throughout the period of eruption of the Tertiary and early Pleistocene lavas'.

Primitive volcano lavas at the periphery of Mount Suswa are cut by the grid-faults; and since both Shackleton (1955) and Baker (1958) consider most of the movements to have ended before the Upper Pleistocene, the earliest eruptions of the volcano can also be dated as pre-Upper Pleistocene. However, most of the Mount Suswa flows are unaffected by block faulting, the faults gradually dying out as they approach the volcano from the south. This feature has been noted by Willis (1936), Baker (1958) and McCall (1967) at other volcanoes in the Kenya Rift Valley. McCall & Bristow (1965) claim that the relation 'cannot, in the case of Mount Suswa, be definitely proved'. There is, however, clear evidence of north–south fault scarps cutting the distal (southern) edges of flows but dying out when traced northwards so that the same flows are unaffected by faulting.

The grid faults southeast of Mount Suswa also rapidly change their trend and converge into the volcano before finally disappearing. This situation is analogous to the fault-pattern surrounding Timber Mountain Caldera in the western United States, where north–south Basin-Range faults also curve towards the caldera centre (Christiansen, Lipman, Orkild & Byers 1965; Cummings 1968).

4. PRIMITIVE SHIELD VOLCANO

(a) *Morphology of the Shield*

Sodalite-bearing phonolitic lava flows make up most of the low-lying, primitive, shield volcano, and they are easily recognized on aerial photographs by their radial distribution around the mountain summit.

The primitive shield is oval with a longer ENE axis of approximately 20 km, a shorter axis of approximately 17 km, and a total area of about 270 km^2. Some of the earlier flows, however, extend up to 9 km beyond the foot of the mountain, forming a fringe at the eastern and southern periphery. A fringe may also be present along the north and west sides, but if so, it is concealed by alluvium. Extrapolation of the outer slopes of the volcano shows that the summit of the primitive shield was never higher than 2100 m, with the Rift floor at 1525 m (in the south) and 1615 m (in the north). In an east–west cross-section, therefore, the cone has an average slope of about 3°. The predominance of lava flows, the oval shape of the cone, and the low angle of inclination of the outer slopes corroborate the conclusion of McCall & Bristow (1965) that the primitive volcano of Mount Suswa is essentially a 'shield volcano', and not a strato-volcano as stated by Richard (in Richard & Neumann Van Padang 1957).

Volcanic activity appears to have been centralized by maintenance of eruptions at points on a linear fracture in the block-faulted basement. The oval shape of the cone suggests, however, that this fracture is related to transverse cross-faults in the basement, and not to the dominant north–south fractures.

Most of the exposed lavas were erupted from central vents at the summit of the primitive volcano that were later engulfed by cauldron collapse. The prominent fan-shaped outcrop at grid-reference 600:760,† however, probably originated from a satellite vent, the position of which is marked by the breached cinder cone at 645:762. Another south flank flow, at 650:717, is also probably satellitic since it shows a prominent flow margin around its entire outcrop. Small low-lying, coulée-type extrusions are also found on the eastern flank at 680:835.

(*b*) *Morphology of the flows*

The primitive volcano flows are tabular and uniform in thickness; they show steep flow margins and smooth arcuate outlines in plan (figure 16). Earlier flows are more voluminous than later ones and many of them show spoon-shaped outlines on subhorizontal parts of the Rift floor (for example, at grid reference 790:800). None of the later lavas reach the base of the mountain. This change from early, voluminous flows, to later, less-extensive lavas, is admirably illustrated during the ascent of the track on the northeast outer flank when at least four prominent flow margins must be scaled. Six primitive volcano flows are exposed in cross-section in the northeast, outer caldera wall (figure 10, plate 8). From oldest to youngest they are approximately 25+, 6, 25, 12, 12 and 17 m thick; these values are representative of thickness for most primitive volcano lavas.

Surface structures on the primitive volcano lavas are of two distinct types. The twofold division of flows in figure 16 is based on this difference, later lavas showing 'globule-surfaces' not seen on earlier flows. Surfaces of the earlier flows are glassy, abruptly convoluted, and ramified with numerous, irregularly shaped vesicles. Loose, subrounded fragments of vesicular lava, up to 0.5 m in diameter, are sporadically distributed on the tops of flows; many of these surfaces show ill-defined rills, repeated at intervals of a few centimetres, lying parallel or perpendicular to the direction of flow.

(*c*) *Heterogeneous glassy rocks*

Many glassy rocks on Mount Suswa are heterogeneous, showing microscopic textures of an unusual character. The most common heterogeneous rock type is composed of globules of lava. This rock has been discussed in detail in an earlier publication (Johnson 1968) and here it will only be dealt with briefly. Other varieties of heterogeneous rock however, similar to those described by McCall (1965) from 'froth flows' in various parts of Kenya, will be considered in greater detail.

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† A reference grid is plotted on the geological map (figure 16). The first set of digits of each grid-reference refers to latitude, and the second to longitude (based on Metric Grid (East Africa) Zone H).

The globule rock is found in two settings: in the upper parts of primitive volcano lava flows, termed 'globule-surface' lavas; and constituting the entire volume of a few uniform sheets, 0.5–1 m thick, termed 'globule flows' (see figure 16). The globule rock is dull-grey to dark buff in colour, well-compacted, and easily dented by a blow from a hammer. Especially characteristic are cellular, subrounded or lenticular patches of material which range from microscopic dimensions up to about 5 cm in length. Most of the larger patches are flattened parallel to flow surfaces. The rock shows columnar jointing, with polygonal cross-sections ranging in diameter from 4 or 5 cm to about 0.5 m.

In thin section the jointed rock is seen to consist principally of globules, mainly 0.05 to 3 mm in diameter, with open spaces between them. The globules are closely packed and most of them are moulded on to each other. Each globule has a highly vesicular, crystalline core, and a thin, continuous, enclosing rim of dark brown glass containing numerous opaque grains. The cellular patches of material visible in hand specimens are the cores of larger globules (up to 5 cm in length) that contain abundant irregularly shaped vesicles.

The origin of the globule-surfaces is attributed to vesiculation that disrupted the tops of the lava flows. The source of the globule flows is unknown but it is suggested they may be globule-surfaces which slipped off the lava flows and extended farther downslope (Johnson 1968).

[*Note.* Flow edges of lavas immediately west of the Kedong River are obscured by faulting, and the mode of emplacement of these flows is therefore uncertain. However, since many of them show 'globule-surfaces' identical to undisputed Mount Suswa flows, it is possible they originated from the central vents of the volcano. On the other hand, it is possible that there are flood lavas with globule-surfaces in the immediate vicinity of Mount Suswa. Because of this ambiguity, these flows are shown in figure 16 as 'lava flows with globule-surfaces', and labelled with a question mark. Similarly, cases where globule-surfaces are absent are shown as 'lava flows lacking globule-surfaces' and, again, are labelled with a question mark.]

Other varieties of heterogeneous glassy rocks on Mount Suswa show vesicular patches, layers and lenses, ranging from microscopic dimensions up to 1 or 2 cm in width, which give a drusy or banded appearance to the lavas. These rocks are common in primitive volcano flows, most abundant in later 'ring-feeder' lavas, and less common in post-caldera flows. They are found either at the chilled tops and bottoms of flows that have massive crystalline centres, or in lavas which are glassy throughout.

In thin section the rocks are characterized by two, more or less distinct, areas of contrasting texture: (1) vesicular patches, layers and lenses which are coarsely crystalline and correspond to vesicular areas seen in hand specimens; (2) less vesicular, continuous areas which are glassy and enclose the crystalline patches, layers and lenses. The crystalline areas show abundant alkali feldspar laths, with some opaque grains, and minor amounts of interstitial ferromagnesian minerals and glass; many of the feldspar laths form fringes around the periphery of the areas. In contrast, the poorly vesicular, glassy matrixes contain more opaque grains, and smaller feldspar laths.

These textures indicate that in the more rapidly cooled portions of many flows there was a tendency for certain parts to favour crystal- and bubble-growth more than others. Since crystal- and bubble-growth take place more easily in liquids of low viscosity,† it is suggested

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† The terms 'viscosity' and 'fluidity' will occasionally appear in the text. They are used loosely and are not meant to imply that the lavas necessarily behaved as Newtonian liquids, that is, those with a constant 'true viscosity' or 'true fluidity' at different rates of shear.

that, at the time of eruption, the viscosity of the patches, layers and lenses was less than that of the matrix; and, moreover, since viscosity is a function of volatile content, that the heterogeneous texture of the rocks may have resulted from an irregular distribution of volatiles.

McCall (1965; in McCall & Bristow 1965) recognized heterogeneous glassy rocks in Mount Suswa lavas at the top of one flow in the northeast, outer caldera wall, and on surfaces of some Ol Doinyo Nyukie lavas (post-caldera flows described in § 6). In the first case McCall (1965) described the texture as 'eutaxitic', with 'an incipient heterogeneity in a manner more conspicuous in the flows of Menengai'; the Ol Doinyo Nyukie rocks were said to be similar (McCall & Bristow 1965). Numerous textural types have been described by McCall (1965) from flows on Menengai, and from other areas in the Rift Valley, some of which appear to be identical to the Mount Suswa rocks described above. The 'eutaxitic' varieties on Menengai, however, were described as 'megascopically indistinguishable from rocks called ignimbrites by other geologists', and in discussing their origin McCall proposed that the rocks were produced by vesiculation of lavas in which the volatiles had an irregular distribution caused by stirring in the conduit and laminar flow on the surface.

The interpretation given above by the present writer for the Mount Suswa rocks closely follows that suggested by McCall. However, it is necessary to emphasize that none of the heterogeneous rock types on Mount Suswa could be mistaken for 'ignimbrites' (welded ash-flow tuffs), 'nuées ardentes' deposits, or ash-flow deposits which have undergone 'laminar viscous flowage' (Schmincke & Swanson 1967). The Mount Suswa phonolite rocks are vastly different in texture and mode of occurrence to the pyroclastic sheets described from other volcanic provinces, and the problem of their origin is clearly separable from the genesis of ash-flows as described by Ross & Smith (1961).

(*d*) *Lacustrine sedimentation and a period of quiescence*

During Pleistocene times, extensive sedimentation took place in Rift Valley lakes considerably larger than their present-day counterparts (figure 2). South of Nakuru—the apex of the regional upwarp (see introduction)—these lakes occupy shallow basins which descend in steplike fashion as far as Lake Magadi.

Njorowa Gorge is the Pleistocene overflow channel of Lake Naivasha (Thompson & Dodson 1963; figure 2), and sediments issuing from it were swept southwards across the plains north of Mount Suswa to lap against the flanks of the primitive volcano. They were then deflected to the southeast around the periphery of the volcano, and finally were deposited in the Kedong Basin depression between the present-day Mount Suswa and the eastern Rift escarpment. The depression—forming part of a depositional site called 'Lake Suess' (Gregory 1896)—is limited to the south by a wedge formed by the Kedong cross-fault scarp and a high, prominent grid-fault immediately west of, and parallel to, the present-day Kedong River (figures 2, 16). The sediments are found in outcrops up to tens of metres in height in dry stream sections of the Kedong river; they are well-bedded, light buff to maroon, coarse-grained, and largely of volcanic origin. To the south, the Kedong River section bends abruptly in a double turn through Barajai Gorge (figure 2), linking the Kedong Basin with Tiridik Gorge, and representing the overflow channel of 'Lake Suess' to the south (Sikes 1926).

The walls of wide outwash gullies extending northward from Mount Suswa on to the soil-covered Akira ranchland, consist exclusively of well-bedded alluvium. Also, in the gorges low on the north flank of the volcano, a variety of sedimentary and pyroclastic beds are intercalated with 'globule flows' and thin lavas from Mount Suswa. These beds consist of fresh grey pumice lapilli, dark brown pumiceous ash, and earthy pulverulent alluvium. The source and mode of transport of much of this material is unknown, but probably most of it originated from sources beyond Mount Suswa and was deposited by fluvial and aeolian influx associated with the 'Lake Suess' sedimentation. The possibility cannot be excluded, however, that some—especially the fresh grey pumice lapilli—was ejected from vents on Mount Suswa, and it is therefore concluded that the primitive volcano may have been characterized by explosive activity at some stages during its construction, and not exclusively by the effusion of lava flows.

A period of quiescence ensued after the primitive volcano was built. This led to dissection of the cone. An eroded land surface is exposed low on the north flank where it is mantled by later pyroclastic deposits; these beds are cut by present-day streams that characteristically follow the precaldera drainage pattern. Dissection affected only the lower outer slopes of the volcano since the land surface profile is not exposed in the caldera wall.

Periods of quiescence are known in many volcanoes where cauldron collapse and explosive volcanic activity have subsequently taken place (see, for example, Williams 1941). Mount Suswa is no exception for the next major event on the volcano was the collapse of the summit of the primitive cone and the eruption of large volumes of pumice and lava.

5. EVENTS AT THE TIME OF CAULDRON SUBSIDENCE

(a) *Introduction*

One of the most difficult problems in elucidating the geologic history of a volcanic region is determining the relationship between eruptions and associated periods of faulting and subsidence; on this depends the assessment of the relative importance of two intimately related processes:

(i) Collapse of a magma chamber roof into voids produced by removal of magma during volcanic activity.

(ii) Faulting and collapse which link an underlying magma chamber with the ground surface, change equilibrium conditions in the magma, producing volcanic activity.

Since these two processes are also of fundamental consideration in the problem of the origin of calderas, particular attention will be given in the following description to the precise relations between periods of eruption, formation of ring fractures, and cauldron subsidence. Much of the geological detail at the caldera wall of Mount Suswa is presented in a series of diagrams (figures 5 to 13). The origin of the Mount Suswa caldera will be discussed later, in § 8, where a review of the caldera problem is given and the structural relationships of the Mount Suswa caldera are discussed in detail.

(b) *The caldera*

The caldera is bounded by a steep, inward-dipping escarpment, and occupies a roughly oval area of about 83 km^2. Its ENE axis is about 12 km long and lies parallel to both the longitudinal axis of the primitive cone and the direction of cross-faulting in the plateau basement; the shorter, NNW axis is about 8 km long. Near-horizontal, pre-caldera primitive volcano lavas are exposed at one section in the caldera wall (figure 11, plate 9), and at two other localities where their identification is less certain (figures 7, 9, plates 5, 7). Elsewhere, the caldera rim is mantled by products erupted during cauldron subsidence, or by post-caldera lava flows (figure 16).

The height of the escarpment above the caldera floor ranges from 0 to 200 m, but is mostly between 110 and 160 m. The floor of the caldera consists entirely of post-caldera lavas; nowhere inside the depression can collapsed remnants of the primitive volcano be identified. Even in subvertical exposures of the ring graben walls that extend 100 m below the caldera floor, the only flows exposed are post-caldera in age. Taking the altitude of the primitive cone as 2100 m above sea level, the subsidence can therefore be estimated as exceeding 700 m. Cauldron collapse took place mainly along a single ring fault producing the prominent caldera wall. However, a single escarpment is absent in the northern sector of the caldera; here, the extrapolated lines of the caldera wall from the east and west are displaced producing gently southward-dipping terrain (see figure 12).

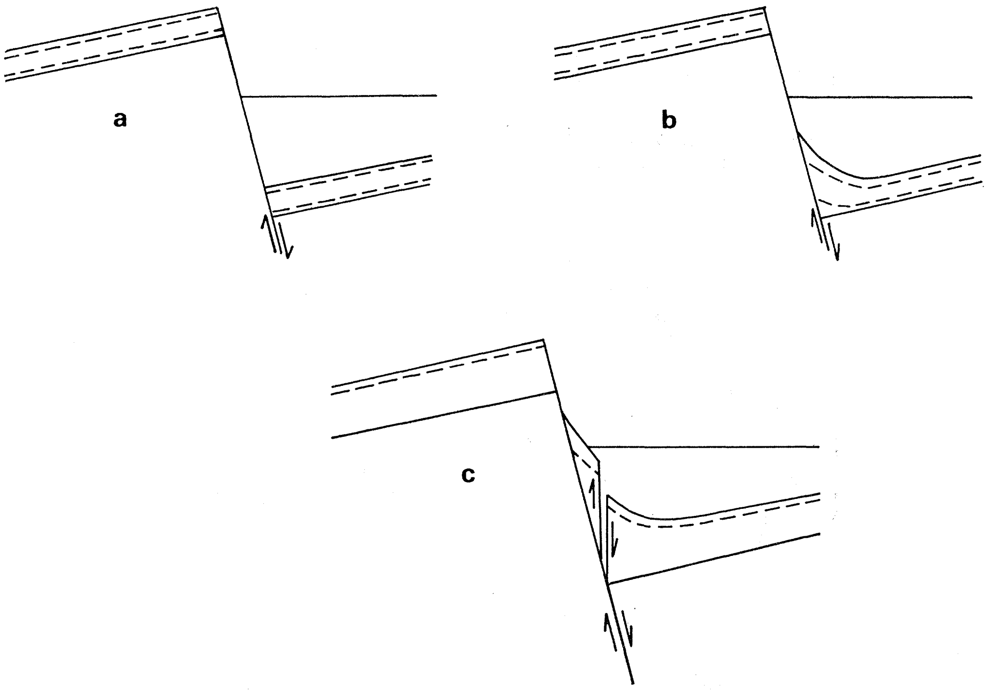

FIGURE 4. Schematic sections through caldera walls. (*a*) Pumice mantle truncated by caldera fault; (*b*) pumice mantle *apparently* truncated by ring fault, but at depth—below the level of post-caldera infilling—beds are inclined against the caldera wall, indicating deposition after cauldron subsidence; (*c*) pumice beds visibly inclined against the caldera wall, but at depth cut by secondary, steeply inclined faults formed by post-depositional movements of the cauldron block.

(*c*) *Early pyroclastic eruptions*

The earliest eruptions at the time of cauldron subsidence produced a distinctive layer of pyroclastic rocks. These deposits are exposed, in outcrops up to 2 m thick, on the northern, eastern and southern outer flanks of the volcano where they constitute an excellent stratigraphic marker horizon between primitive volcano and post-caldera lavas.

The layer consists of pumice fragments (less than 2 cm in diameter) with local concentrations of tabular alkali feldspar crystals and small, black glass flakes, set in a fine-grained, yellow to buff-coloured, semiconsolidated and carbonate-rich matrix. The coherent nature of the material, and the absence of lateral or vertical grading and sorting contrasts with later bedded pumice deposited on the western slopes. Occasional inclusions of black, vesicular, glassy lava fragments are also found, especially in thicker outcrops near the periphery of the cone. Many surfaces also show polygonal, infilled mud cracks.

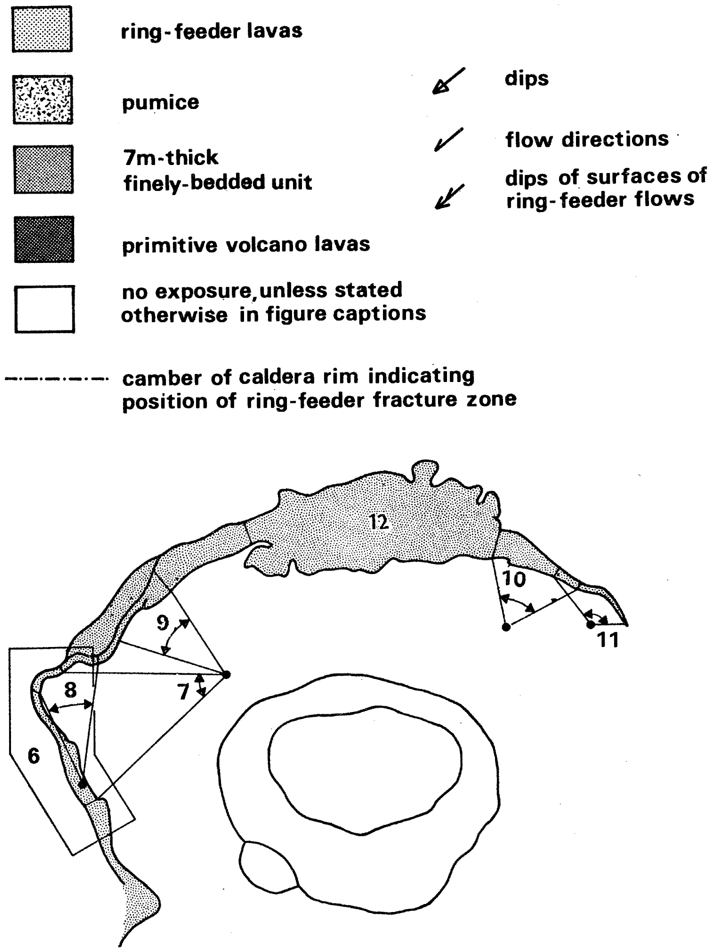

Figure 5. Index for caldera wall diagrams (figures 6 to 13). The lower map of the caldera shows the fields of view for figures 7 to 11, and the areas covered by figures 6 and 12.

These features indicate that the pyroclastic debris was probably deposited by 'rain lahars' (Cotton 1952) in which the constituent particles were intimately mixed when material moved as mud flows to the periphery of the primitive cone, incorporating loose fragments of lava from underlying flows. Most exposures show single lahar units, but at a few places high on the northeast outer flank, dark, fine-grained, air-fall ash, 1 to 3 cm thick, can be found separating two lahar horizons.

At the Kedong River, the lahars overlie the thick sequence of sedimentary rocks that occupies the southern part of the 'Lake Suess' sedimentary basin. The lahars are also well-exposed on the northern flank of the volcano, but when traced to the northeastern wall of the caldera (figures 10, 11, plates 8, 9), they change from unbedded deposits to well-laminated, sub-horizontal beds consisting of accretionary lapilli (0.25 to 1 cm in diameter), and vesicular,

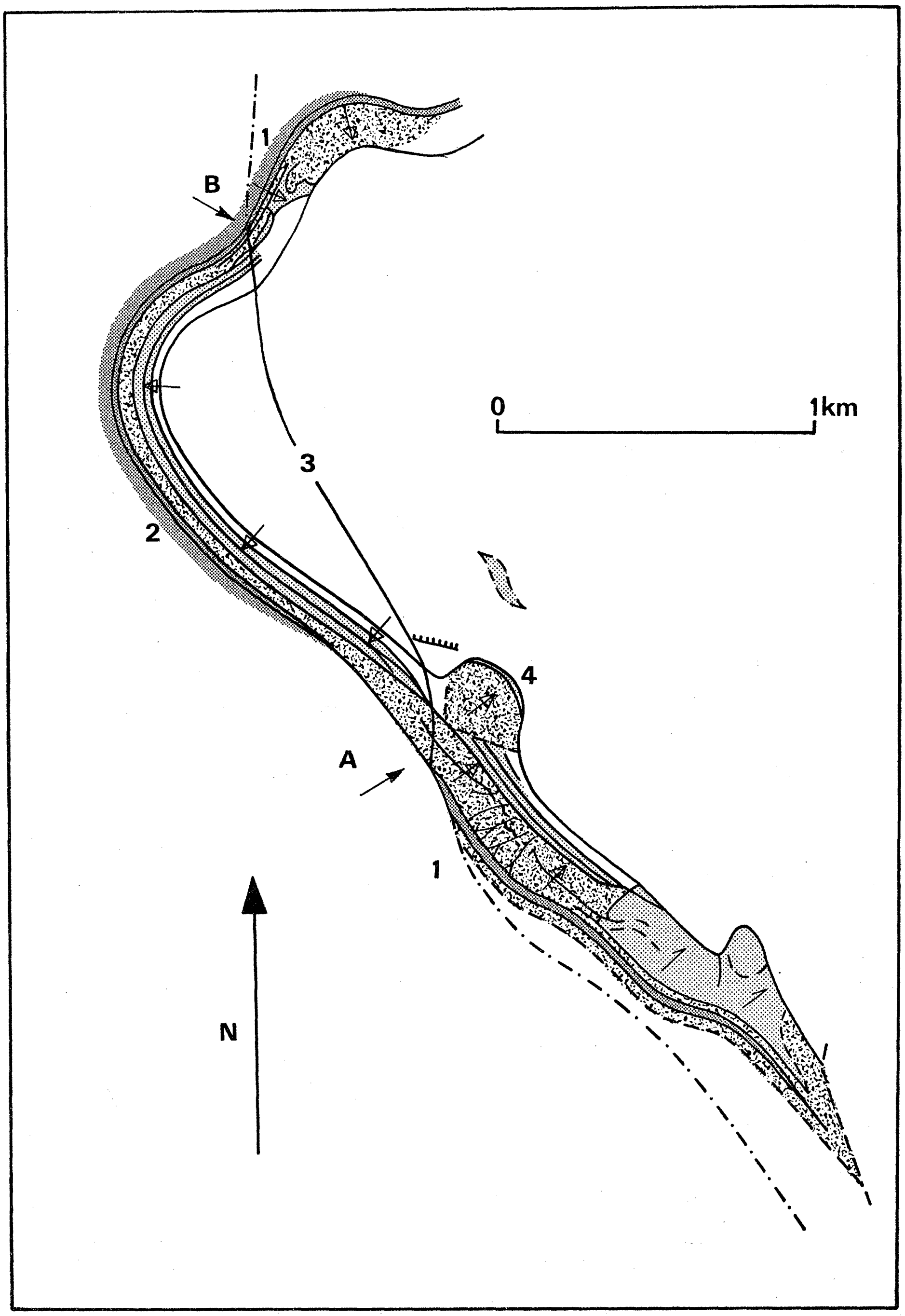

Figure 6. Map of scalloped embayment in western caldera wall. A and B are cross-over points of the caldera escarpment and ring-feeder fracture zone. South of A and north of B (1), the ring-fracture zone lies west of the caldera escarpment; ring-feeder lavas and pumice beds exposed in the caldera wall dip into the caldera. Between A and B (2), the camber of the caldera rim is absent, and lavas and pumice dip outwards to the west. The solid line (3) represents the extrapolated line of the ring-fracture zone across the caldera floor. 4 is a collapsed segment of ring-feeder lava, mantled by undisturbed, inward-dipping, pumice beds. (For further details, see figures 1, 7 and 8.) Collapse of the embayment postdated both the main cauldron subsidence and eruption of the older ring-feeder lavas. The age of the embayment collapse relative to deposition of the pumice mantle is uncertain; but if the ring-feeder lava at 4 subsided at the same time as the embayment, then pumice deposition must have postdated collapse since the pumice beds mantle the collapsed segment and rest undisturbed against the caldera wall.

black ash fragments (rarely greater than 1.5 cm in diameter). The beds range from dust layers, less than 1 mm thick, to ash beds that reach a maximum thickness of about 25 cm. The presence of accretionary lapilli suggests that the bedding of the deposits is due to subaerial accumulation and not subaqueous deposition of reworked material (Moore & Peck 1961).

There is no direct evidence to show if eruption of these early pyroclastic deposits was before or after formation of ring faults and cauldron subsidence.† Although in the northeast outer caldera wall they appear to be truncated by the caldera ring fault (figures 4a, 11) it is equally possible that at depth the beds are inclined against the caldera escarpment having showered on to an earlier, steep caldera wall and cascaded down to the base of the escarpment (figure 4b).

(*d*) *Development of ring fractures*

In contrast to the earliest deposits, the depositional attitude of later, much more voluminous material shows that ring fractures and a caldera escarpment had formed before eruptions took place. This later material includes large volumes of pumice—deposited mainly on the western outer flank—and 'ring-feeder' lavas erupted from a fracture zone concentric with and outside the caldera escarpment.

The position of the outer ring-fracture zone is marked by a prominent camber formed by surfaces of ring-feeder lava flows that dip away from the ring fracture (figure 3). The camber is absent in the western part of the caldera where a later collapse feature produced a scalloped embayment that extends beyond the line of the outer ring-fracture zone (figure 6 and figures 7, 8, plates 5, 6). Eruption of the ring-feeder lavas clearly postdated formation of the caldera escarpment since all the flows dip into the depression, and many of the later flows completely cover the fault scarp.

Since there is little or no displacement along the outer ring-fracture it is probable that, instead of a single continuous fault, there is a series of discontinuous or en-echelon fractures. This is also suggested by features in the walls of the scalloped embayment. Here, at two points where the caldera escarpment and the line of the outer ring fracture cross one another (A and B on figures 6, 7, 8), there are no feeder dykes or fractures exposed beneath truncated ring-feeder lava flows.

At several places along the caldera rim, a well-defined soil-covered terrace lies between the steeper outer flanks and the camber of the caldera rim. This terrace may be a depositional feature formed by ring-feeder flow surfaces. Alternatively, it could mark the position of outer members of a wider ring-fracture zone.

Just as the extrapolated lines of the caldera wall from the east and west are en echelon in the northern part of the caldera, so too are the concomitant ring-fracture zones. The terrain here is faulted, irregularly southward-dipping, and composed almost entirely of ring-feeder lavas. A prominent pumice-filled depression, usually soil-covered, is present between the two zones of ring-fracture (figure 1, plate 4 and figure 12).

North–south linear fractures on the northern outer flanks of the volcano also produced flows similar to the ring-feeder lavas. The position of one prominent fissure is shown by a line of 15 cumulodomes that extends in a broken chain from the caldera rim down to the Rift floor (figure 16). Lava flows low on the southern outer slopes may also have been derived from linear flank fissures, although here only one satellite vent has been identified (670:717).

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† On the index to the geological map (figure 16) the deposits are arbitrarily shown predating cauldron subsidence.

(*e*) *Ring-feeder lava flows*

Ring-feeder lavas outcrop mainly on the upper slopes of Mount Suswa in exposures that circumscribe the summit of the primitive volcano. The lavas are easily distinguished from primitive volcano flows since they all overlie the lahar horizon and none display 'globule-surfaces'. Most of the ring-feeder lavas are found as thick tabular flows that rarely extend more than 3 km from the caldera rim. Numerous coulées and small cumulodomes represent protrusions of lesser volume and more bulbous form immediately above or close to the fissures or central vents that erupted them.

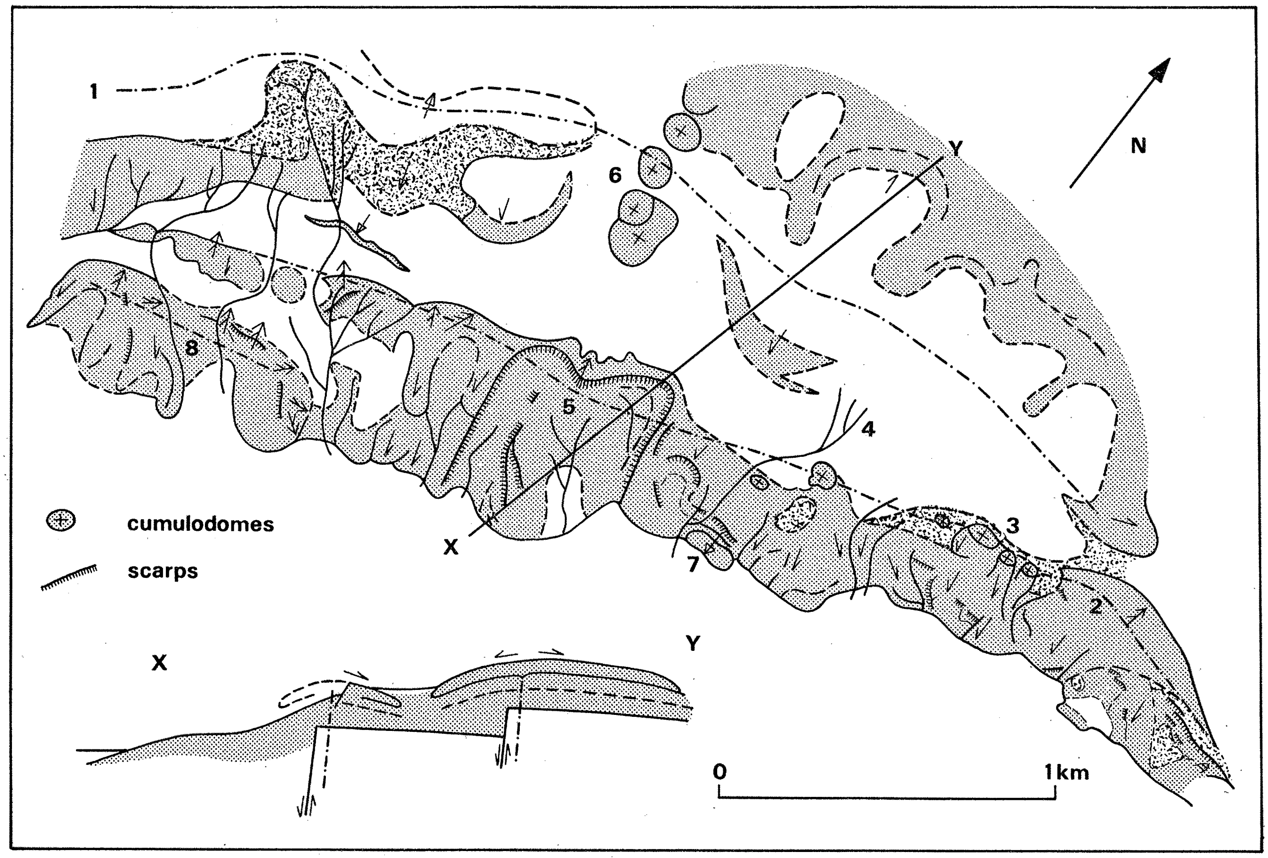

FIGURE 12. Map of northern caldera sector, showing offset relationship between extrapolated lines of the caldera wall and ring-fracture zone. The ring-fracture at 1—located in the east by tracing the camber of the caldera rim—erupted ring-feeder lavas on to the northern outer flank. The ring-fracture at 2 is marked to the west by the line of cumulodomes (3) and the crests of coulées; lavas from this fracture flowed mainly to the south. The trough between the two ring-fracture zones is soil-covered, but in stream sections at 4 it is seen filled with pumice. Minor collapse sectors complicate the southern belt of ring-feeder lavas. The largest sector, at 5, shows two faults parallel to the line of cumulodomes at 6. An isolated tilted block at 7 dips 70° into the caldera. A third feeder-fracture of limited extent parallels the two main ring-fracture zones (8).

Cross-sections through most ring-feeder flows reveal textures that indicate the viscous nature of the lava at the time of extrusion. A prominent but crude banding, resulting from myriads of small, irregularly shaped vesicles, lies subparallel to flow surfaces. Locally, intense flow convolutions are developed, many of which show rotation of included fragments. In other places distension of lava during flow has formed drawn-out spicules that extend into dilation cavities. Rubbly scoriaceous lenses also show jagged druses between highly irregular clots of vesicular lava that range from microscopic sizes to several centimetres in diameter. Surface structures of ring-feeder lavas are the same as those found on lavas of the early primitive volcano group: loose subrounded fragments of vesicular lava are sporadically distributed across a contorted, vesicular, and often crudely corrugated surface.

In contrast to the thick voluminous lavas, there are many spatter beds exposed on the caldera wall which are very thin (1 to 1.5 m). These extend laterally from a few metres to over a kilometre. Many of them show a basal layer of pumice-breccia consisting of angular, agglomerate-size pumice fragments, slightly moulded on to one another.

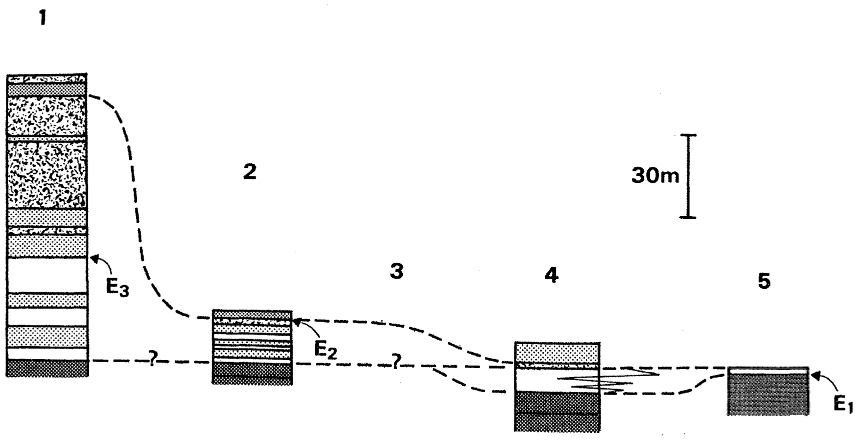

FIGURE 13. Sequences of ring-feeder lavas and associated pyroclastic rocks at the caldera wall of Mount Suswa. (1) Western caldera wall (figure 7): thick bedded pumice deposits, with 7 m thick, finely bedded unit near top of sequence, overlying earlier series of ring-feeder lavas. (2) Northwest caldera wall (figure 9): reduced thickness of pumice beds, with finely-bedded unit occupying rim exposures. (In 1 and 2, identification of primitive volcano lavas is uncertain; deposits of the early pyroclastic eruptions appear to be absent.) (3) Northern caldera sector (figure 12): ring-feeder lavas, younger than pumice beds of section 1, obliterate older rocks. (4) Northern caldera wall (figure 11): ring-feeder flow overlies beds of ash and accretionary-lapilli produced by early pyroclastic eruptions (and a thin pumice horizon); the beds give way to lahar deposits on the outer flank (5). Erosion surfaces: E_1, pre-caldera dissection; E_2, mantle bedding of finely-bedded unit (figure 9); E_3, scourings beneath ring-feeder flow (figure 7).

When the ring-feeder lavas flowed down the caldera escarpment, collapse features were produced that were dependent upon the inclination of the scarp and fluidity of the lava. The thick ring-feeder flow in figure 11, plate 9, for example, was so viscous, and the caldera wall so steep, that when lava moved over the fault scarp it collapsed into the caldera leaving an irregularly truncated flow. This same section also illustrates how different horizons within a single flow varied in their fluidity and how they responded differently to flow down the steep fault scarp. Later minor faulting and erosion of the caldera escarpment have also produced lava scarps which are often difficult to distinguish from those formed by collapse during flow.

In thin section, ring-feeder lavas are characterized by a predominance of alkali feldspar laths and opaque grains with interstitial brown glass of various shades of colour; they show a general deficiency of groundmass ferromagnesian minerals compared to totally crystalline lavas of the primitive volcano and post-caldera periods. Flows of uncertain status are found in two sections of the caldera wall (figures 7, 9, plates 5, 7). These could be ring-feeder lavas, but since they are more coarsely crystalline and uniform than is usual, they are thought to be primitive volcano flows.

(*f*) *Bedded pumice deposits*

Extrusion of ring-feeder lavas was accompanied by eruption of large volumes of pumice. A westward wind seems to have blown at the time, since most of the ejecta was deposited on the western flank of Mount Suswa producing a mantle that extends continuously from the caldera rim down to the soil-covered Rift floor. At the western caldera rim the mantle reaches a maximum exposed thickness of about 60 m, but when traced laterally on to the northern and southern slopes it thins and disappears entirely on the eastern flank (figure 13). At the western caldera wall, the pumice beds are concordant with the camber of the rim and are banked against the escarpment, sometimes completely mantling it.

The pumice deposits vary from dust and fine ash, in beds from less than 1 mm to 30 cm thick, to light grey lapilli (1 to 4 cm in diameter) in beds a few centimetres to 2.5 m thick. Subordinate amounts of subangular lithic fragments of non-vesicular crystalline lava are also present. At most levels, thin, fine-grained beds, frequently dark brown in colour and of earthy appearance, alternate with thicker beds of coarser pumice, some of which show graded bedding. Seepage of ground-water through the pumice mantle at the western caldera wall is temporarily arrested by the thin, fine-grained layers. These frequently show trona† encrustations on surfaces exposed to the atmosphere, and limonitic seepage lines immediately below their bases.

Numerous, closely spaced, steep-sided gullies cut deeply into the pyroclastic cover of the western flank giving a characteristic 'badland' drainage pattern (figure 1, plate 4). Subaerially deposited pumice beds are exposed in most of the gullies, but at outcrops in flat-bottomed stream sections, close to the soil cover of the Rift floor, the effects of fluvial reworking are shown by earthy, pulverulent, well-sorted and current-bedded pumiceous sediments that were washed down from higher slopes.

The succession of coarse and fine-grained pumice-beds in the pyroclastic mantle is more or less uniform throughout the sequence, except at the western caldera rim where, in the upper part of the succession, there is a distinctive pyroclastic unit 7 m thick. This unit consists mainly of fine-grained ash beds, up to 15 cm thick, and thin dust layers usually less than 1 cm thick. The beds constitute rim exposures in the west and northwest parts of the caldera (figures 8, 9, plates 6, 7), but they thin along the southwest escarpment and are overlaid by thicker beds of coarser pumice (figures 6, 13 and 7, plate 5). Owing to erosion, they may be traced only for short distances on to the western outer flank and down the inclined pumice banking.

All the pumice beds are found in smooth-surfaced outcrops that mantle the ring-fracture zone, lying undisturbed against the caldera fault scarp. They do not show linear or cone-like accumulations immediately above the fissures, nor any obvious lateral grading of grain size away from them. Therefore, although the statement of McCall & Bristow (1965) may in part be correct that pumice was erupted 'from sources along the caldera fracture zone' the possibility cannot be excluded that much of it may also have originated from vents inside the caldera, now buried by post-caldera infilling.

In figure 16 most of the ring-feeder lavas exposed on the outer slopes of Mount Suswa are shown as post-dating the thick pumice deposits of the western flank. At the western caldera wall, however, the pumice mantle overlies an earlier succession in which ring-feeder lavas are again

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† An efflorescent, hydrated sodium carbonate salt ($Na_2CO_3.HNaCO_3.2H_2O$); X-ray powder photograph identification.

predominant (figure 7, plate 5). There is, therefore, a general sequence from an early period of ring-feeder flows, to one characterized by explosive eruptions, to a final period in which ring-feeder flows were again dominant (see also figure 13).

(*g*) *Depositional features of ring-feeder lavas and pumice deposits*

Figures 6 to 12 describe in detail parts of the outer caldera of Mount Suswa. Each section illustrates the depositional attitude of ring-feeder lavas and pumice deposits with respect to the caldera escarpment: pumice beds are shown inclined against the caldera wall, in places completely mantling it; ring-feeder lavas dip into the caldera, some extending down the pumice banking.

Although later collapse on a new fracture produced the western embayment—a local and relatively minor feature compared to the rest of the caldera (figures 6 and 7, 8, plates 5, 6)—there is no visible evidence of significant main caldera fault movements following deposition of the pumice banks. Step faults and slump structures are absent, and spatter beds covering the caldera fault (for example, 3 in figure 8) are unaffected by later movements. The possibility must be considered, however, that the inclination of the main caldera fault and the depth of the caldera floor are such that movements after deposition of the pumice beds were taken up on later, steeper fractures exposed only beneath the level of post-caldera infilling (figure 4*c*). However, if such faults are present, their displacements cannot be very great since the unconsolidated pumice beds would probably show more evidence of slumping and sliding due to their unstable position. Moreover, if the caldera wall is steeper than shown in figure 4*c*, and approaches a vertical position, later subparallel faults would be easily recognized above the level of post-caldera infilling.

Minor collapse structures are shown on the northern caldera rim in the later group of ring-feeder lavas (figure 12). Small collapse sectors, bounded by ENE faults parallel to the main caldera ring fault, and NNW faults parallel to the line of cumulodomes on the north flank, indicate minor adjustments above the main ring-fracture subsequent to the ring-feeder lava eruptions.

6. Post-caldera eruptions

The final eruptive episode on Mount Suswa produced lavas that originated mainly within the caldera. These lavas partly filled the caldera, overflowed the lowest part of the rim, and extended down the southern and eastern slopes as long, narrow flows which contrast in form with the more tabular and thicker lavas of the earlier episodes (see figure 16). The post-caldera lavas also show pahoehoe surfaces which are absent on the earlier flows. Toward the end of the post-caldera period a prominent pit crater and ring graben formed inside the older caldera.

The post-caldera succession may be divided into two parts: (*a*) an earlier group of non-porphyritic lavas and lavas in which sparse tabular, soda-sanidine phenocrysts are present; (*b*) later, Ol Doinyo Nyukie lavas containing abundant, rhombic, anorthoclase phenocrysts.

The earlier group of flows is exposed within the caldera and on the southeast outer flank of Mount Suswa (figure 16). The oldest exposed flow inside the caldera is a congealed lava lake which, in the walls of the ring graben, shows a thickness of at least 60 m; the upper surface constitutes the flat floor of the caldera, but the base is not exposed. Later flows were erupted from vents on a linear fissure in the northeast part of the caldera floor, marked by a row of lava cones. The first of these lavas were thin and became ponded against the northeast caldera escarpment, but later lavas overflowed the eastern caldera wall and extended down the outer flanks to the Kedong Basin in a series of overlapping lobes. An extensive network of collapse holes and anastomosing lava tubes is developed in the later flows immediately east of the caldera rim; these structures have been described in detail by Williams (1963) and Glover *et al.* (1964).

The age of the early post-caldera lavas on the southeast outer flank, relative to those within the caldera, is unknown since later Doinyo Nyukie lavas have concealed any possible overlap. These same Doinyo Nyukie flows have also covered the sources of the early post-caldera lavas on the outer flanks.

The last period of vulcanicity on Mount Suswa was marked by eruptions of porphyritic, Doinyo Nyukie lavas. Most of the flows issued from a single, central vent in the southwestern part of the caldera, giving rise to Ol Doinyo Nyukie volcano ('The Red Mountain'), a cone rising more than 500 m above the caldera floor. Several satellitic eruptions later broke through the flanks of Ol Doinyo Nyukie, and the main summit vent was widened to form a pit-crater.

Ol Doinyo Nyukie volcano is roughly elliptical in plan, its long, northwest–southeast axis running tangential to the later ring graben. The base of Ol Doinyo Nyukie in the northwestern wall of the ring graben overlies a prominent pyroclastic horizon consisting of finely bedded, light-brown to black ash fragments (less than 0.5 cm in diameter) and angular fragments of alkali feldspar. The horizon is about 30 m in maximum thickness, but it thins rapidly eastwards and is missing along the northern, outer wall of the ring graben.

Satellite-vents on the flanks of Ol Doinyo Nyukie have produced two prominent lava flows (consisting of several flow units) and a number of small lava cones. The flow exposed low on the northwest flank of Ol Doinyo Nyukie originated from a vent a few tens of metres west of the northwest edge of the ring graben and flowed northwards and westwards on to the caldera floor. The age of the ring graben collapse, relative to the time of eruption of the flow, therefore remains uncertain since the flow is not cut by the ring fault (figure 1, plate 4 and figure 16). The second flow was erupted from a fissure, at least 1.5 km long, which trends towards the summit of Ol Doinyo Nyukie and is cut off by the outer fault of the ring graben. The line of this fissure is marked by a row of about thirty lava cones (figure 1). The feldspar phenocrysts of both satellite-vent flows are generally smaller and more tabular than those in the lavas making up the main cone. A third satellite-vent flow is probably present on the inaccessible 'island-block' inside the ring graben.

The most recent flows on Mount Suswa, although younger than the ring-graben, are similar to Doinyo Nyukie lavas in containing abundant phenocrysts of anorthoclase. The sporadic cover of vegetation and the freshness of the lavas suggests that these flows are probably only 100 or 200 years old. One lava outcrops in the base of the ring graben and has a crescentic plan owing to flow in two opposite directions from a hidden vent on the floor of the graben. The other lava outcrops on the southern outer flank of Mount Suswa and was erupted from a north-south fissure.

After eruption of the last flow from the summit of Ol Doinyo Nyukie the main vent was enlarged to form a prominent pit crater. This enlargement may have been caused by peripheral collapses into the vent, or by cylindrical subsidence along a ring fault of small diameter. The pit crater is approximately 460 m deep and is truncated on its northeastern side by the later ring graben. The remnant features of the crater indicate that it was originally elliptical in plan, the perimeter nearly 5 km in length, its longest axis (1.6 km in length) tangential to the later ring graben.

7. RING GRABEN

The second major collapse on Mount Suswa took place entirely within the older caldera and produced an annular trench or 'ring graben' which lies slightly towards the southeast rim of the caldera. In contrast to the earlier cauldron collapse, formation of the ring graben was not accompanied by eruption of lava flows or pyroclastic material (McCall 1963).

The ring graben consists of two, more or less concentric, fault scarps bounding a steep-sided, annular zone of subsidence (figure 1, plate 4). It cuts deeply into the post-caldera lavas of the outer caldera floor, truncates the pit crater, and isolates an oval, flat-topped and steep-sided 'island-block' (McCall & Bristow 1965), with a circumference of 10.5 km, a maximum diameter of 3.75 km and a minimum diameter of 2.5 km. The block is tilted a few degrees to the northwest, and its southeastern and northwestern edges are slightly upwarped. Most of the island-block surface lies below the level of the surrounding inward-facing fault scarp rim. Step-faults and slumped segments of Ol Doinyo Nyukie lavas are preserved along its northern edge. Thick vegetation makes the block extremely difficult to reach and traverse on foot, and only the northern rim has been mapped by the writer.

The width of the ring graben varies from 500 m in the north to 1.8 km in the southeast. In the northern part, the height of the outer fault scarp ranges from 90 to 215 m, and at the precipice beneath Ol Doinyo Nyukie summit it reaches a maximum of about 520 m. These variations in height are caused by the variable topography of the graben floor and the gradual rise of the outer escarpment rim toward the summit of Ol Doinyo Nyukie. The southern part of the graben floor is flat due to partial filling by the crescentic, post-ring graben flow. The surface of the flow decreases in altitude and width to the northwest and northeast tips of the crescent between which, in the north, the topography is irregular and rugged. Here, high ridges are found covered by extensive talus deposits consisting of boulders up to about 4 m in diameter.

The northern flanks of two en echelon ridges in the northeastern part of the ring graben show rare outcrops of non-vesicular, dense, crystalline phonolite characterized by a lamination that dips northward at 20 to 50°. In thin section, the lamination is seen to be due to parallelism of groundmass feldspar laths, accentuated by hydrothermal alteration, which gives a coarse banding composed of alternating dark and light streaks and irregular lamellae. Tabular alkali feldspar phenocrysts are frequent, and rounded, non-laminated patches (less than 1 cm and up to 10 cm in diameter) of material identical in mineral-content to the enclosing matrix, are occasionally found which show gradational contacts with the fissile matrix. Because of its distinctive appearance (and slightly different mineral-content) compared to lavas in the opposite wall of the ring graben, it is believed the rock may be intrusive and that the ridges which it constitutes are inclined blocks of a ring intrusion that was emplaced before collapse of the ring graben.

A coarse agglomerate consisting of subrounded boulders, up to about 3 m in diameter, set in a dull grey to brown, earthy, pulverulent matrix, is restricted entirely to the walls of the ring graben (figure 16). The boulders consist of Ol Doinyo Nyukie lavas, lavas of the earlier post-caldera period, and laminated 'ring-intrusion' rocks. The agglomerate appears to have been formed by explosions which took place along ring fractures, triturating the wall rocks, and causing detached blocks to become rounded. Subsequent collapse along the same fractures left fault scarps coated with agglomerate.

Although the surface of the island-block and the rim of the outer ring graben wall both consist of Ol Doinyo Nyukie lavas, no individual flow on the central block has been correlated with a counterpart across the ring graben. Moreover, as emphasized by McCall & Bristow (1965), there is no remnant of the steeper parts of the main cone of Ol Doinyo Nyukie on the opposite rim of the island block (see figure 1, plate 4). Therefore, although it is possible that the surface of the block is the direct continuation of the outer caldera floor across the ring graben, evidence to support this has not been found.

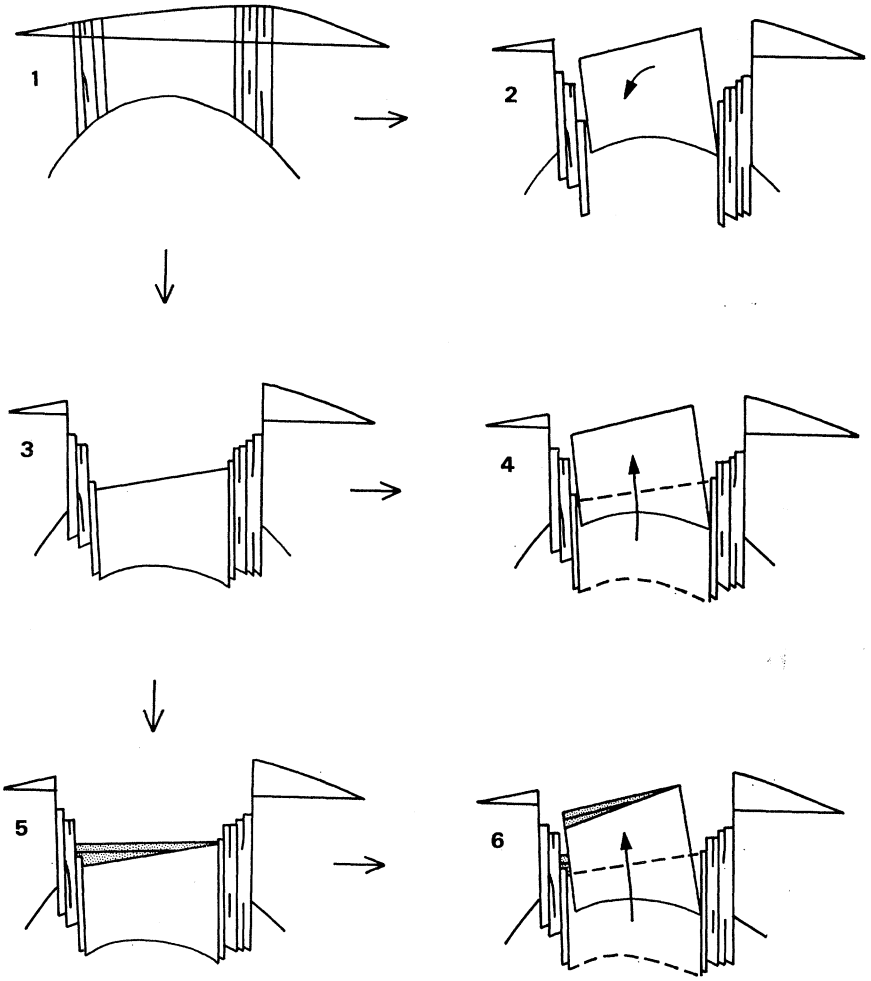


FIGURE 14. Three mechanisms leading to formation of the ring graben; for explanation, see text.

Since the structure of the central island-block is, at present, unknown, discussion on the origin of the ring graben must remain speculative. Three possible mechanisms, however, are presented in figure 14. In all three cases, a zone of ring-fracture (5.5 km in maximum diameter, about 1 km wide, and of unknown inclination at depth) is formed, extending from the top of the magma chamber to the ground surface; explosions produce agglomerate at the outer and inner cylindrical surfaces of the ring-fracture zone (stage 1 in figure 14). The zone of ring-fracture probably formed at an early stage in the post-caldera eruptive episode since the main vent of Ol Doinyo Nyukie and the inferred source of the lava lake exposed in the northern wall are both situated close to the ring graben. It is also possible that the fractures may have formed by rejuvenation of a set of ring faults in the older cauldron block upon which the post-caldera lavas had accumulated.

The first mechanism in figure 14 involves preferential collapse of rocks in the ring-fracture zone; this may take place by arcuate slices subsiding at different times in different parts of the zone. The central block becomes isolated, and it tilts, jamming between the outer wall of the ring graben (2 in figure 14). This process would be enhanced if magma first intruded the fracture-zone to form a ring-intrusion. The ring-fracture zone could then sink more easily since it is composed of dense, intrusive rock heavier and more massive than the lava flows. As stated earlier, the en-echelon ridges in the northern part of the ring graben are possibly the tilted blocks of a ring intrusion emplaced before collapse. Subsidence of the ring-fracture zone would also be enhanced by the presence of the unconsolidated agglomerate which would reduce resistance to collapse at the inner and outer ring fracture surfaces.

In the second mechanism, a caldera is formed by subsidence along the ring-fracture zone. The cauldron block is then uplifted into its present position, preserving an annular trench (3 and 4 in figure 14).

The third mechanism is similar to the second except that, after cauldron collapse, eruption of Ol Doinyo Nyukie lavas takes place from vents on the floor of the caldera, masking irregularities of the original surface. Uplift then produces a flat-topped island-block composed of lavas which do not correspond to those of the outer rim (5 and 6 in figure 14).

The last two mechanisms show similarities to the concept of 'resurgence' introduced by Smith & Bailey (1962, after van Bemmelen 1939). 'Resurgent cauldrons' are volcanic depressions that show central up-domed horsts on the floors of calderas; moat-like trenches separate these uplifts from the older, outer caldera wall. Resurgence is believed to be due to emplacement of intrusive bodies at depth. The central island-block of Mount Suswa, however, lacks the apical, linear, graben structures that characterize the resurgent blocks of Valles and Creede calderas in the San Juan Mountains of the western United States (Smith, Bailey & Ross 1961; Ratté & Steven 1967).

8. CALDERAS

In this section, the origin of the Mount Suswa caldera and the general problem of the origin of calderas will be discussed. First, processes leading to the formation of explosive magmas and ring-fractures will be described. This will be followed by a discussion on the ways in which these processes may be related to one another, and to mechanisms of cauldron subsidence. Finally, a consideration of the origin of the Mount Suswa caldera, the problem of 'Krakatau-type' calderas will be discussed.

(*a*) *Relations between explosive eruptions, formation of ring-fractures and cauldron subsidence*

Explosive magmas

The most important properties that cause magma to behave explosively are high volatile content and high viscosity, and rapid rates of volatile exsolution (Verhoogen 1951).

Only a brief statement is necessary here concerning processes of volatile enrichment in magmas, and it must suffice to mention only the two most important theories, namely: (*a*) the controversial 'retrograde boiling' principle of Morey (1922), whereby crystallization of magma causes concentration of volatiles in the residual melt; and (*b*) Kennedy's concept that water in a magma must diffuse upward and outward to environments of low pressure and temperature to maintain a constant water vapour pressure throughout the chamber (Kennedy 1955).

Reductions in fluid-pressure, causing rapid vesiculation of magmas, may be produced by any of the following processes:

(i) Build-up of magmatic pressure in the chamber causes magma to be intruded into fissures, or through older feeder channels in the chamber roof. When fissures reach the surface, pressure is relieved and the magma vesiculates.

(ii) Development of ring fractures causes pressure-release (Reynolds 1956), and eruptions from the ring faults predate, are synchronous with, or postdate cauldron collapse. The subsiding cauldron block may also force underlying magma up the bounding fractures (Clough, Maufe & Bailey 1909), contributing to further eruptions and to the opening of new fissures and additional pressure releases.

(iii) Withdrawal of magma to deeper levels causes decrease in pressure in the upper parts of the chamber and vesiculation takes place (MacDonald 1961).

The entry of meteoric water to the chamber may also be considered as a process leading to explosive fragmentation of magmas (see, for example, Williams 1953). Water may be admitted through fissures and by percolation, and magma is disrupted as the water turns to steam.

Ring fractures

Ring fractures bounding calderas may be formed either by downwarping and collapse into, or doming above, magma chambers. If there is an increase in magmatic pressure, causing doming of the chamber roof, then inward-dipping 'cone-sheet' fractures may be produced (Anderson 1936), along which later subsidence may take place (Reynolds 1956; Smith, Bailey & Ross 1961; MacDonald 1965; Roberts 1966; Taubeneck 1967). Downwarping, on the other hand, leading to the formation of vertical or outward-dipping ring fractures and to cauldron collapse, may be caused by one, or a combination, of the following processes:

(i) Withdrawal of magma to deeper levels producing (*a*) a void into which the unsupported chamber roof collapses, or (*b*) 'sucking down' of the chamber roof by receding magma (Oftedahl 1953). The difference between these two processes is that in the first, only the weight of the cauldron block is responsible for collapse, while in the second, a drop of pressure inside the chamber—caused by magmatic withdrawal—establishes a pressure-difference between the atmosphere and the chamber interior; this produces an additional downward hydraulic effect on the overlying roof.

(ii) Gravitational foundering of a dense chamber roof into underlying, static, liquid magma. This process—often referred to as cauldron collapse of 'Glencoe-type' (after Williams 1941)—was first proposed by Clough *et al.* (1909) in their pioneer investigation of Glen Coe caldera, Scotland.

(iii) Rapid evacuation of a chamber due to eruption of pyroclastic material from central vents, and subsequent collapse of the chamber roof into the underlying void. This is the classic, caldera-forming principle of van Bemmelen (1929), later developed by Williams (1941), to which the name 'Krakataun' (often spelled 'Krakatoan') has been applied.

Formation of ring fractures by downwarping—as in the case of fractures formed by doming—need not necessarily be accompanied by cauldron collapse, and subsidence of the cylindrical block may only take place after or during magmatic stoping of the ring fractures. Stoping will tend to widen and loosen the contact between the block and wall of the cauldron, thereby reducing frictional resistance to collapse.

Discussion of relations

There are many possible sequences of events relating explosive eruptions to the formation of ring fractures and cauldron collapse. To avoid further written descriptions, the principal sequences are presented graphically in figure 15. This 'flow-diagram' is largely self-explanatory, and it conveniently illustrates the complexity of the possible relationships by showing numerous paths in which a caldera may form starting from one of the following primary processes: (i) withdrawal of magma to lower levels; (ii) gravitational foundering into static magma; (iii) eruptions at central vents; (iv) doming of chamber roof by underlying magma.

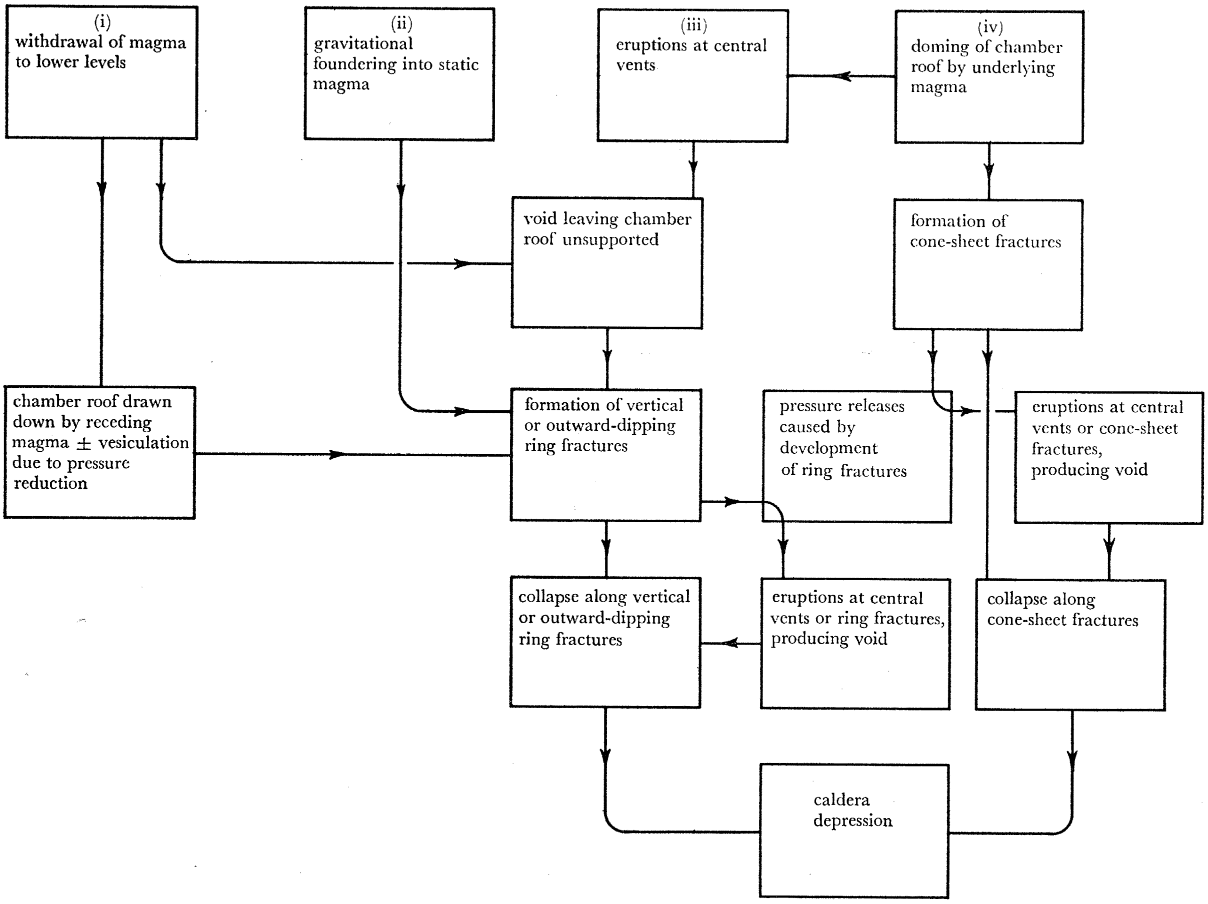
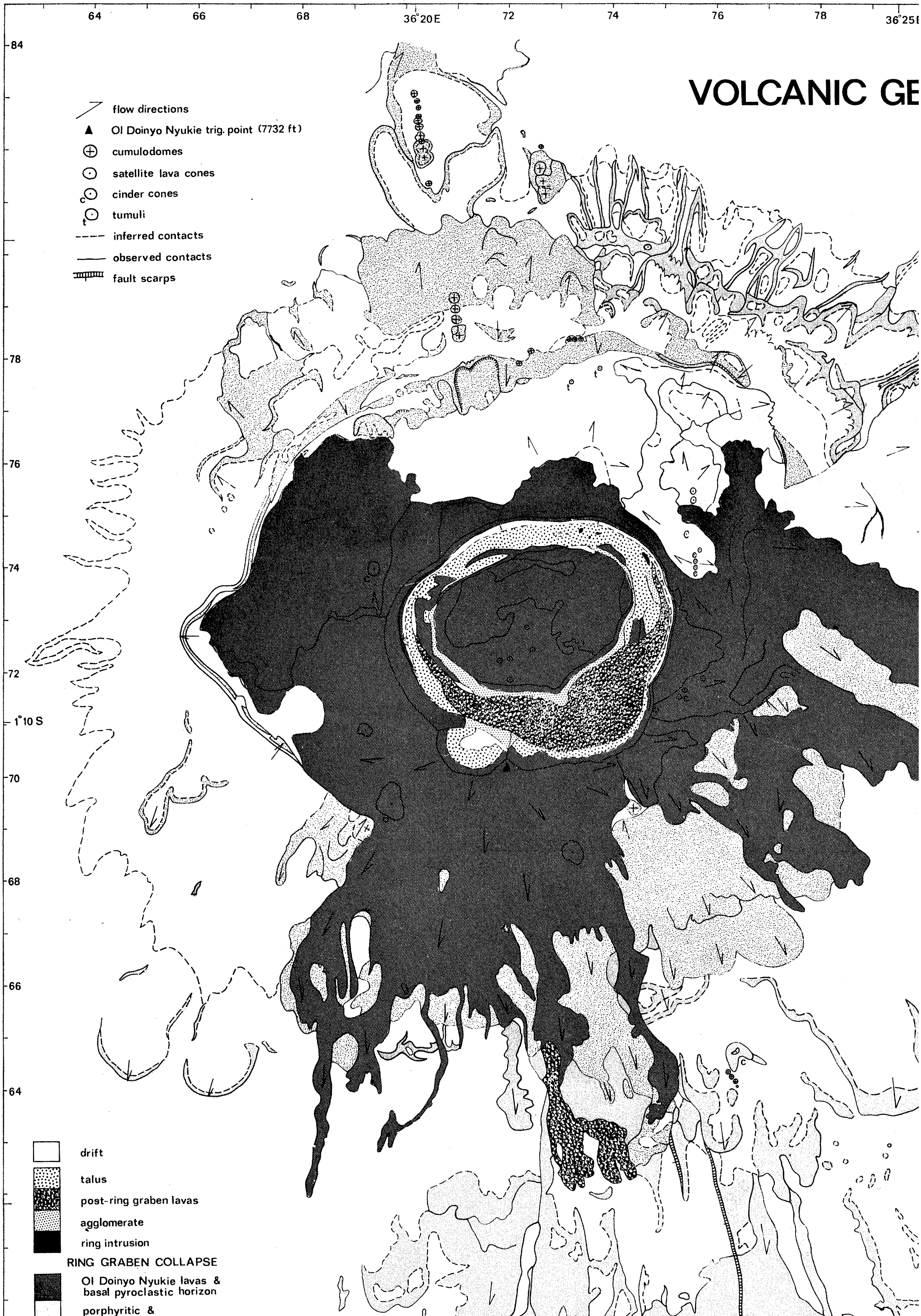


FIGURE 15. Sequences leading to formation of a caldera.

Clearly, however, the diagram is oversimplified, and many alternative sequences could be described, involving combinations of more than one path and the influence of other processes. For example, although slight withdrawal of magma may produce a void so that ring fractures form by downwarping, the subsequent collapse may be due mainly to gravitational foundering into the underlying melt. Or again, after formation of ring fractures, successive explosive eruptions may be due in part to meteoric water percolating down the ring faults.

VOLCANIC GE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flow directions
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RING GRABEN COLLAPSE
Ol Doinyo Nyukie lavas & basal pyroclastic horizon
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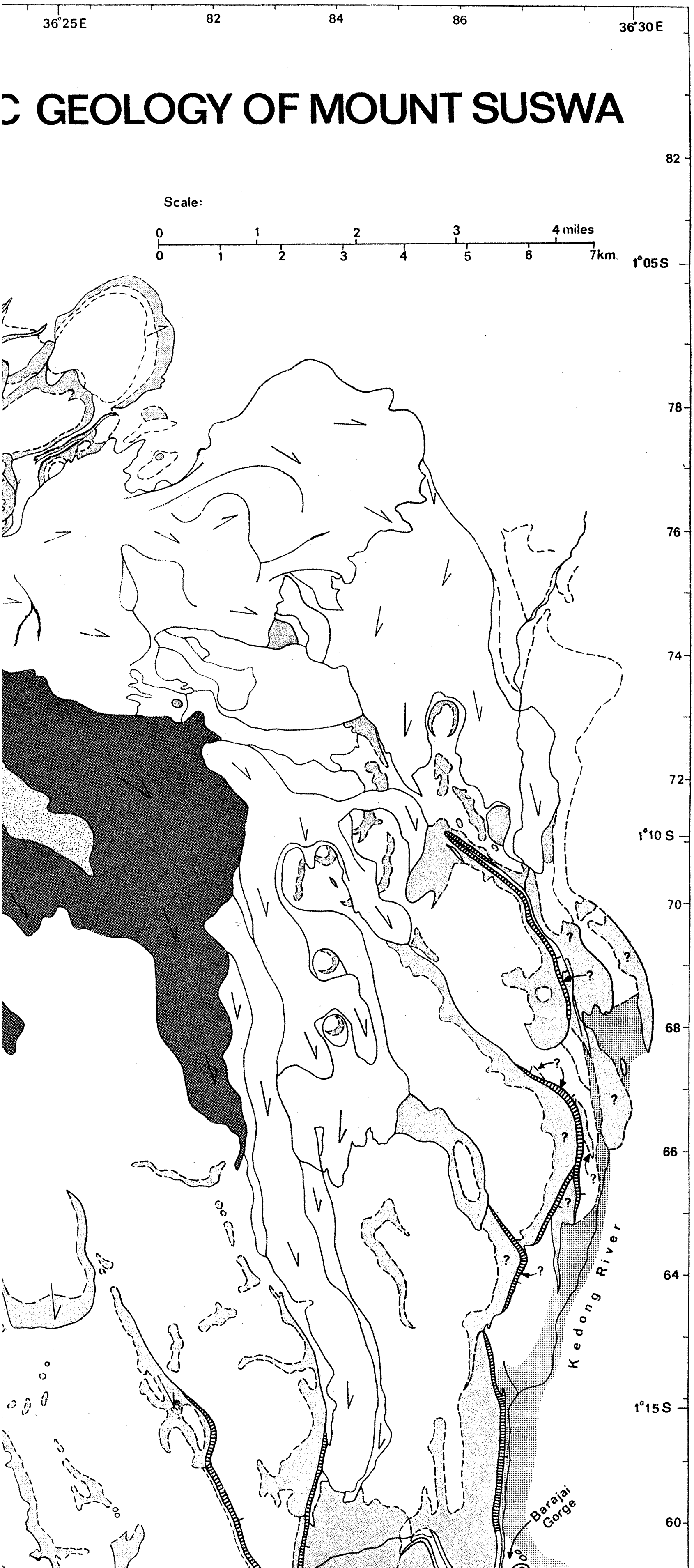
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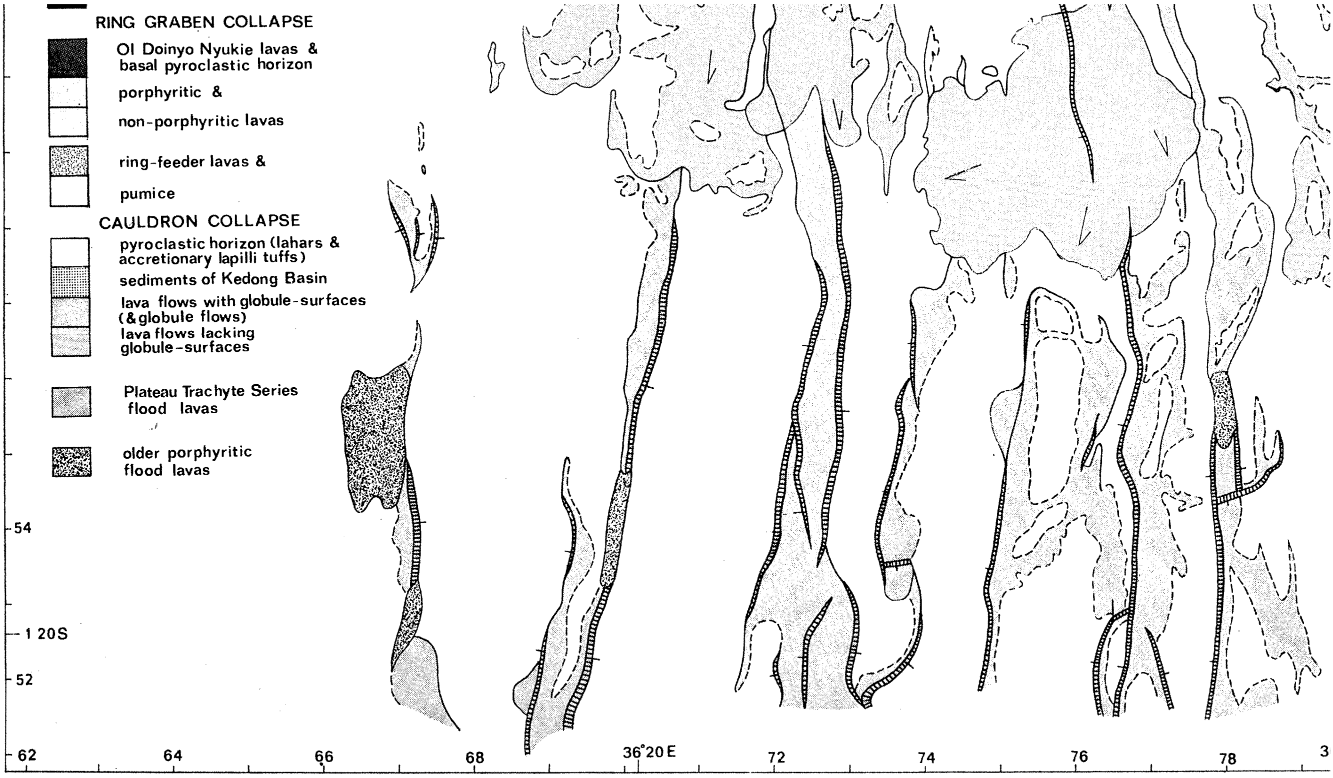
RING GRABEN COLLAPSE
Ol Doinyo Nyukie lavas & basal pyroclastic horizon
porphyritic &
non-porphyritic lavas
ring-feeder lavas &
pumice
CAULDRON COLLAPSE
pyroclastic horizon (lahars & accretionary lapilli tuffs)
sediments of Kedong Basin
lava flows with globule-surfaces (& globule flows)
lava flows lacking globule-surfaces
Plateau Trachyte Series flood lavas
older porphyritic flood lavas
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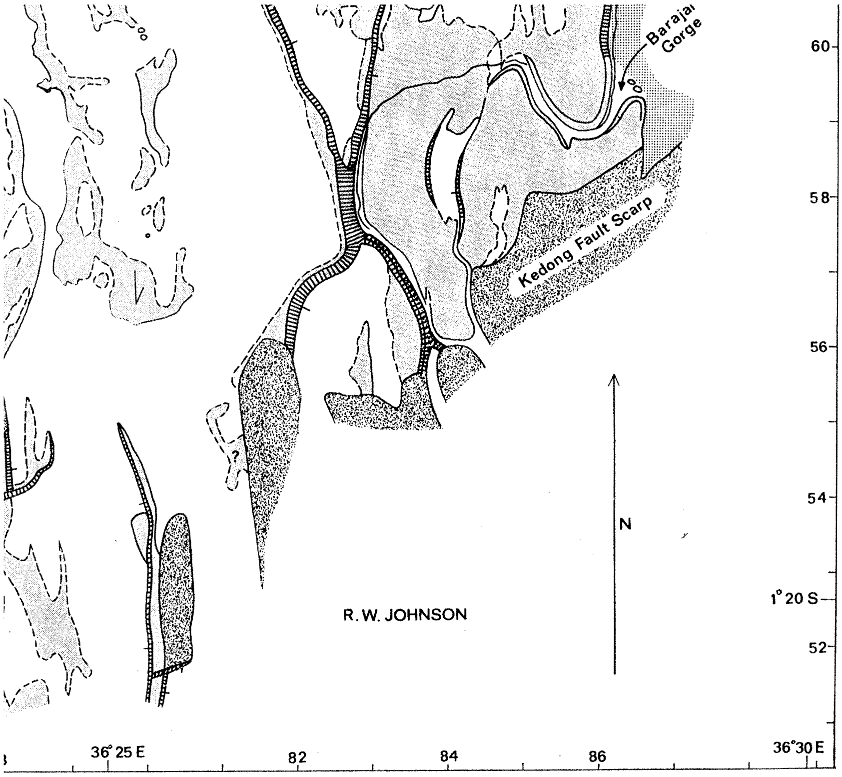
FIGURE 16



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(*Facing p.* 406)

The student of a caldera is therefore presented with a spectrum of closely related processes from which he must select a combination that accounts for the relations observed in the field. It is commonly found, however, that these field observations are insufficient, since the caldera's structures are always exposed at one erosion level, and many critical features are either hidden at depth or removed by erosion. The inclination of ring faults at depth, for example, is never seen in young calderas, and even in eroded structures the attitudes are often uncertain and their significance ambiguous (see, for example, Reynolds 1956; Bailey 1958). Moreover, as illustrated by the following points, the structural relationships that can be observed at surface level in young calderas are also open to more than one interpretation:

(i) Although the pumice mantle of an explosive volcano may seem to be truncated by the caldera wall this does not necessarily imply that formation of ring fractures and cauldron collapse took place after the explosive eruptions.

(*a*) If opening of ring fractures produces pressure releases then the cauldron block may at first be prevented from subsiding as the underlying magma vesiculates and expands. After the eruption dies down, the cauldron block may continue to sink and so truncate the pumice banking (McCall 1963). In this way pyroclastic flows (ash-flows, mud-flows, etc.) may also be preserved in caldera wall exposures.

(*b*) If collapse predates explosive eruptions pumice banked against the caldera escarpment may be buried by later products (figure 4*b*). Erosion of escarpments will also remove pumice beds once inclined against them. In calderas where undisturbed pumice beds rest against and mantle the caldera escarpment it is clear that emptying of the chamber by eruptions was not the cause of cauldron subsidence. In these cases, therefore, development of ring fractures and cauldron collapse may have been responsible for pressure-releases that produced succeeding explosive eruptions.

(ii) Where eruptions and cauldron collapse are synchronous it is impossible to distinguish between (*a*) several periods of subsidence producing pressure-releases each of which causes an explosive eruption, and (*b*) successive eruptions producing voids into which the cauldron block repeatedly sinks. Moreover, it is probable that both of these processes are sympathetically related. An eruption may produce a void into which the cauldron blocks sinks; this subsidence, in turn, causes pressure-release and another eruption follows; the cauldron block again subsides into a void and the cycle is repeated until, either the magma becomes undersaturated with volatiles, or the cauldron block reaches a stable structural position.

This same problem of interpretation also arises in considering the origin of explosions that accompany magmatic withdrawal. If the cauldron block is 'sucked down' by the receding magma, does the accompanying explosive activity at the ring fault result from pressure-release caused by the development of ring fractures? Or is it a direct consequence of pressure reduction in the chamber inherent upon magmatic withdrawal? Or is it both? Clearly, distinguishing these alternative processes by examination of depositional and structural features is, for all practical purposes, an impossible task.

(iii) Pumice eruption may not be related directly to formation of ring fractures and cauldron collapse. Identifying the time interval in such cases will obviously be difficult, especially if later pumice is erupted from vents along the old caldera fault, or from central sources obscured by post-caldera infilling. This applies, not only to examples such as Mount Suswa, but also to calderas which at depth show pumice beds banked against the caldera escarpment.

(*b*) *Origin of the Mount Suswa caldera*

The explosive character of the magma at the time of cauldron subsidence may have been due to any, or a combination, of the processes outlined above. The erosion surface dissecting lavas of the primitive volcano indicates a period of quiescence during which volatiles may have diffused to the upper, cooler parts of the chamber (Kennedy 1955). The crystal-rich character of the early pyroclastic deposits suggests that cooling and crystallization had taken place, tending to produce a volatile-rich magma (Morey 1922). (The presence of phenocrysts would, in any case, enhance vesiculation without a necessary increase in volatile content for, as Verhoogen (1951) has stated, '...it is known that heterogeneous [bubble] nucleation (that is, nucleation at an interface between, say, liquid and suspended crystals) is considerably easier than nucleation in a homogeneous phase...'.) Another possible cause of the explosive behaviour may be influx of meteoric water to the chamber, since lahars and accretionary lapilli of the early pyroclastic deposits and the existence of 'Lake Suess', indicate that the climate at the time of cauldron subsidence was characterized by rainfall heavier than that of today.

The inclinations of the Mount Suswa ring faults at depth are not seen; it is therefore unknown if the fractures originated by doming or downwarping. However, two important features may be emphasized when the possible genetic relations between formation of ring faults, explosive activity and subsidence are considered.

First, in the western part of the caldera, it can be clearly demonstrated that deposition of the thick pumice mantle on the western flank took place after formation of ring-fractures that gave rise to the caldera escarpment and early ring-feeder lavas. The Mount Suswa caldera, therefore, was not formed by the 'Krakataun' mechanism of Williams (1941; subsidence into a void produced by rapid expulsion of pumice from central vents), and the statement of McCall (1963) and McCall & Bristow (1965) that the pumice on Mount Suswa indicates 'weak Krakatoan characteristics' is therefore misleading (Johnson 1966*b*).

Secondly, there is no visible evidence of significant movements of the main caldera fault during or after deposition of the pumice mantle although, as stated earlier, the possibility of such movements cannot be totally discounted.

These observations lead to the conclusion that many eruptions producing pumice and ring-feeder lavas on Mount Suswa may have been generated by pressure-releases caused by development of ring fractures and cauldron subsidence. Most of the explosive eruptions appear to have taken place after cauldron collapse producing pumice that was banked against the caldera escarpment. This is in agreement with the statements of McCall (1963) and McCall & Bristow (1965): '...the opening of the superstructure [by cauldron collapse] causes a sudden pressure release and the volatile-rich residual magma suffers ebullition, surging up ring-fracture conduits' (McCall 1963). 'Pumice eruption [on Mount Suswa] is believed to be secondary and not the primary cause of caldera formation' (McCall & Bristow 1965).

The lavas—and also probably much of the pumice—were erupted from the ring-feeder fracture zone. However, as stated earlier, much of the pumice may also have originated from vents inside the caldera, or from sources on the main caldera fracture.

Three possible primary processes may therefore have produced the Mount Suswa caldera: magmatic withdrawal, gravitational foundering, or doming and later collapse along cone-sheet fractures. Field evidence, however, provides no evidence as to which of these was the dominant process.

(*c*) *Discussion of 'Krakatau-type' calderas*

Calderas formed in historic times—for example, on Krakatau (Judd 1888) and Coseguina (Williams 1952)—and the numerous accounts reporting ash-flow deposits around calderas, clearly illustrate the intimate relationship between voluminous pumice eruptions and cauldron subsidence. There has been, however, an unwarranted tendency to assume that such calderas always form by rapid expulsion of pumice from central vents (the so-called 'Krakatau-type' calderas of Williams 1941, after van Bemmelen 1929), despite the fact that structural and depositional relations are usually open to other equally acceptable explanations.

It has been reasoned that in a caldera believed to be of 'Krakatau-type' the volume of the caldera should be close to the volume of liquid magma removed from the chamber during explosive eruptions (see, for example, Williams 1941). Estimation of these volumes is, however, a notoriously difficult task, and reliable estimates are not numerous.† A recent recalculation of the volume of material (liquid magma, crystals and lithic fragments) erupted from Mount Mazama, Oregon, is 42 km^3, and a value of about 62 km^3 is given for the volume of Crater Lake caldera (Williams & Goles 1968). Katsui (1963) reports 60 km^3 as the volume of material (liquid and lithic fragments) erupted at Shikotsu caldera, Japan, and 80 km^3 for the volume of the caldera. In both of these examples, therefore, the volume of the caldera appears to be greater than the volume of material removed from the chamber.

The problem of volume deficits in calderas is often referred to in the literature, and it presents a major obstacle to advocates of the 'Krakataun' mechanism. In order to account for these discrepancies authors have postulated several accompanying processes, such as, withdrawal of magma to lower levels, intrusion of magma at depth, shrinkage of magma on crystallization, and change of shape of the chamber. However, if eruptions of pumice result from pressure-releases caused by the development of ring fractures and cauldron collapse, then there is no 'space-problem' since the origin of the caldera must be due to causes other than evacuation of the chamber by eruption of pumice from central vents (Johnson 1966*b*).

The primary origin for many so-called 'Krakataun' calderas—as in the case of Mount Suswa—could therefore be any of the three remaining primary mechanisms shown in figure 15, namely, withdrawal of magma, gravitational foundering, or doming of the chamber roof and later collapse along cone-sheet fractures. Whether or not explosive eruptions take place during subsidence may depend entirely upon the state of the magma at the time ring fractures form and pressure releases take place. This conclusion may be taken as an amendment and development of McCall's statement: '...the "Glencoe" mechanism is the primary mechanism involved in the majority of subsidence calderas, and...the "Krakatoan" mechanism is in the nature of a special case, a complication of the "Glencoe" mechanism operating where volatiles are particularly abundant within the magma chamber at the time of subsidence' (McCall 1963).

The problem of the origin of calderas has confronted volcanic geologists since the last part of the nineteenth century, and even though many more calderas have been investigated and the character of the problem has changed over the years, the origin of these depressions still remains an unresolved mystery. Processes that cause cauldron subsidence—like many geological phenomena—do not record themselves readily in the rocks and structures they produce; and

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† In the case of Mount Suswa, no attempt has been made to calculate the volume of material erupted at the time of cauldron subsidence since the base of the deposits is not seen west of the caldera. Owing to post-caldera infilling, the floor of the caldera is unexposed, and therefore the volume of the caldera is also unknown.

coupled with the hindrances of observation, the problem of genetic interpretation becomes extremely difficult. Attempts to fit calderas into *genetic* schemes of classification therefore seem wholly futile, for there are few calderas where one mode of origin can definitely be said to exclude, or dominate over, another, while there are many calderas in which alternative processes may be equally acceptable.

It seems preferable, therefore, that each caldera be examined on its own merit. Precise relations between ring faults and pumice deposits must be carefully noted, and possible alternative processes of origin adequately presented. One result of this approach may be that explosive eruptions accompanying cauldron subsidence will be recognized, not as the progenitor of collapse—a concept hitherto dominating the literature, but as the outcome of collapse—a conclusion reached in the case of Mount Suswa caldera.

9. Conclusions

(1) Mount Suswa is a Quaternary, central-type volcano composed of sodalite-bearing phonolitic lava flows and pyroclastic rocks. It rests on the gently sloping floor of the Kenya Rift Valley, a plateau consisting of quartz-bearing, trachyte flood lavas.

(2) Three major eruptive groups may be distinguished: the first produced a primitive, shield-shaped volcano; the second accompanied the formation of a caldera; the third produced lavas which partly filled the caldera, and later built Ol Doinyo Nyukie volcano.

(3) Glassy rocks of many flows are heterogeneous. Many primitive volcano flows show rocks composed of globules of lavas. Others resemble examples from 'froth flows' described by McCall (1965) from various parts of the Kenya Rift Valley.

(4) Rocks produced at the time of cauldron subsidence include large quantities of pumice and a series of lava flows that originated from a fracture-zone outside and concentric with the caldera escarpment ('ring-feeder' lavas). These eruptions were probably caused by pressure releases when the caldera ring fractures formed.

(5) A striking topographic feature of the volcano is a ring graben that isolates an inaccessible central island-block. The origin of the depression is uncertain, but three different mechanisms are suggested.

(6) A review of the caldera problem emphasizes the difficulties in deducing the origin of any one caldera from field evidence. The formation of so-called 'Krakatau-type' calderas is discussed; this illustrates the contention that *genetic* schemes of caldera classification are impracticable, and that calderas should be treated individually when discussing their origin. Careful observations should be made of the exact relationship between ring faults and pumice deposits, and the possibility of alternative collapse mechanisms should be adequately discussed.

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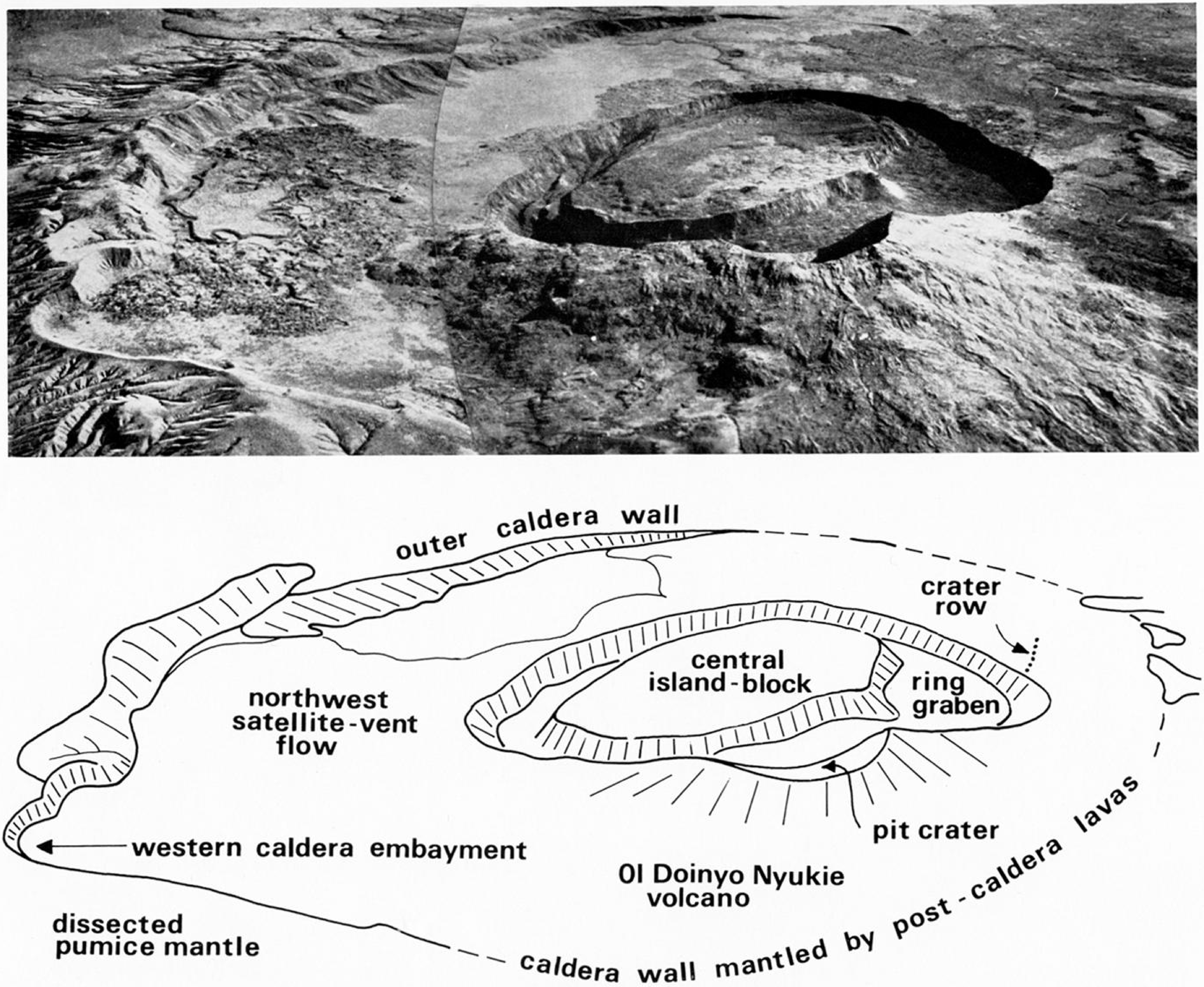

FIGURE 1. Aerial photograph of Mount Suswa caldera and ring graben taken from the southwest; from original photographs by T. A. Tomalin, supplied by P. E. Glover, Nairobi.

FIGURE 7. Embayment in the western caldera wall. Left of A and right of B, ring-feeder lavas dip into the caldera. Between A and B, they dip outwards to the west. The thick extensive flows shown in solid black thin towards. A The lower of the three, thin, poorly exposed flows at 1 is possibly a primitive volcano lava. Sediment-filled scourings are present beneath the flow labelled 2 (erosion surface E3 of figure 13). The pumice mantle of the western flank occupies the upper part of the section. 3 is a conspicuous, inward-dipping spatter bed intercalated with the pumice. The 7 m thick, finely bedded unit (not shown on this diagram for clarity; see figure 6) caps the section right of A. Left of A, it is overlaid by thicker beds of coarser pumice and is traceable, without break, to the extreme left. Photographs by T. Reilly.

Figure 8. Western caldera wall. Line BB′ marks the inferred trace of the ring-feeder fracture on the caldera wall. Left of BB′ (inside the embayment), ring-feeder flows and pyroclastic beds dip outwards to the northwest. Right of BB′, lavas dip into the caldera, and pumice beds are inclined against the caldera escarpment (1), in one place completely mantling it (2). The lavas show a variety of forms: thin 'flows'—probably spatter beds—uniformly cover the pumice banking (3); thicker flows show truncated portions formed by collapse due to viscous flow down steep inclines (4). Left of BB′, truncation of the thick lenticular flow (5) is due to collapse of the embayment. Right of BB′, the initial form of the scarp was probably due to collapse during viscous inward flow, with later modification by erosion. Photographs by T. Reilly.

FIGURE 9. Northwest caldera wall, showing complex of inward-dipping ring-feeder lavas, spatter beds, and bedded pumice, all of which mantle the caldera escarpment (much of the detail on this section is omitted for clarity). The thickest ring-feeder flow (1) dips into the caldera and overlaps two earlier flows which probably belong to the primitive volcano. At the extreme right (2), ring-feeder lavas completely cover the caldera escarpment. In contrast, many of the ring-feeder flows to the left of 2 are truncated, probably due to viscous inward flow down the steep escarpment with later modification by erosion (3). The finely-bedded unit mantles the summit of the escarpment; it dips into stream channels, reflecting the dissected surface on which the ash was deposited (erosion surface E2 of figure 13). The post-caldera, northwest satellite-vent flow is shown in the foreground. Photographs by T. Reilly.

Figure 10. Northeast caldera wall, showing six, near-horizontal, primitive volcano flows (flow thicknesses given in text measured at 1), overlaid by deposits of early pyroclastic eruptions (2; bedded ash and accretionary lapilli). Ring-feeder flow at 3 (also see figure 11) thins out to the left where it is replaced by mantling pumice beds (4). At 5, ring-feeder lava completely covers the escarpment, showing flow scarps on the higher parts of the caldera wall (6).

FIGURE 11. Northeast caldera wall, showing six primitive volcano flows, overlaid by deposits of early pyroclastic eruptions (and a thin layer of coarse pumice). The six flows show no visible intercalated pyroclastic horizons, prominent erosion surfaces, or 'globule-surfaces'. The upper ring-feeder flow has a near-horizontal base, but its upper surface is cambered, with a northerly dip on to the outer flank and a southerly dip into the caldera. Below the dashed line, the ring-feeder lava is massive and columnar-jointed. Above the line, the lava is more cavernous, shows no jointing and, because of greater fluidity at the time of eruption, extends farther down the fault scarp, giving irregular lobes (1), and partial (2) and complete (3) mantling of the primitive volcano lavas. At (4), talus blocks of ring-feeder lava have accumulated.

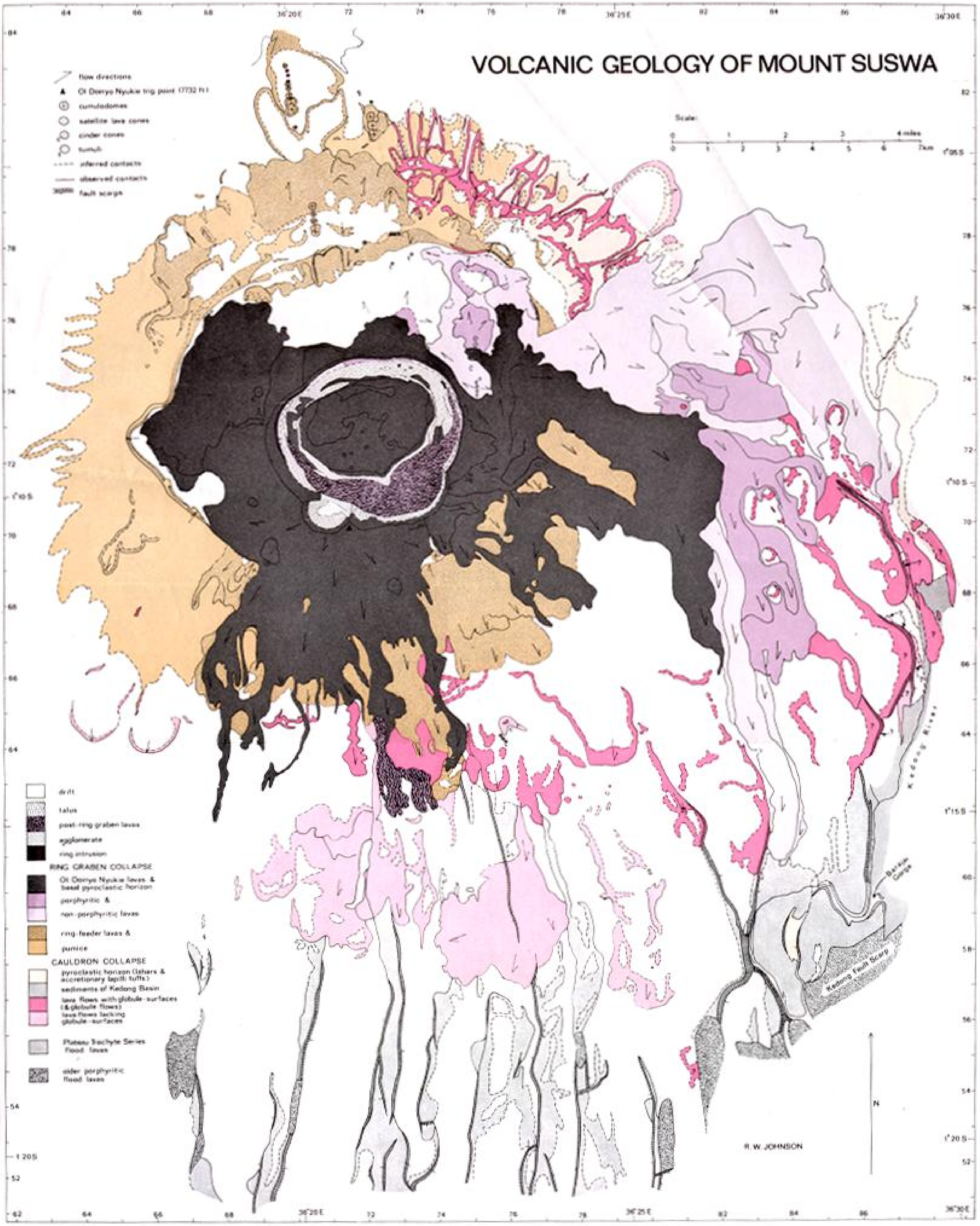

FIGURE 16

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VOLCANIC GE
64
66
68
36°20E
72
74
76
78
36°25
84
78
76
74
72
1°10 S
70
68
66
64
flow directions
▲ Ol Doinyo Nyukie trig. point (7732 ft)
cumulodomes
satellite lava cones
cinder cones
tumuli
inferred contacts
observed contacts
fault scarps
c
t
☐ drift
talus
post-ring graben lavas
agglomerate
ring intrusion
RING GRABEN COLLAPSE
Ol Doinyo Nyukie lavas & basal pyroclastic horizon
porphyritic &

C GEOLOGY OF MOUNT SUSWA

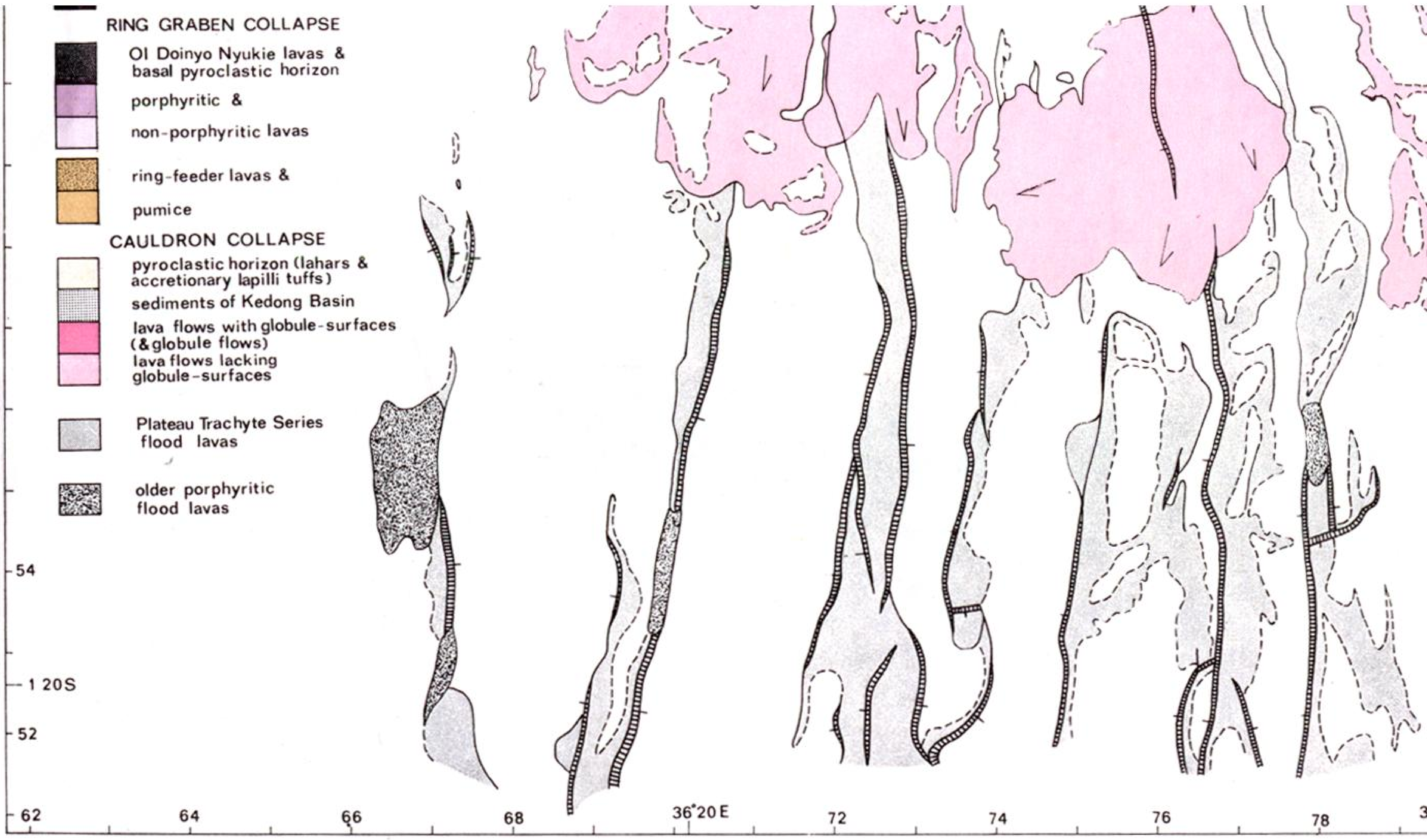
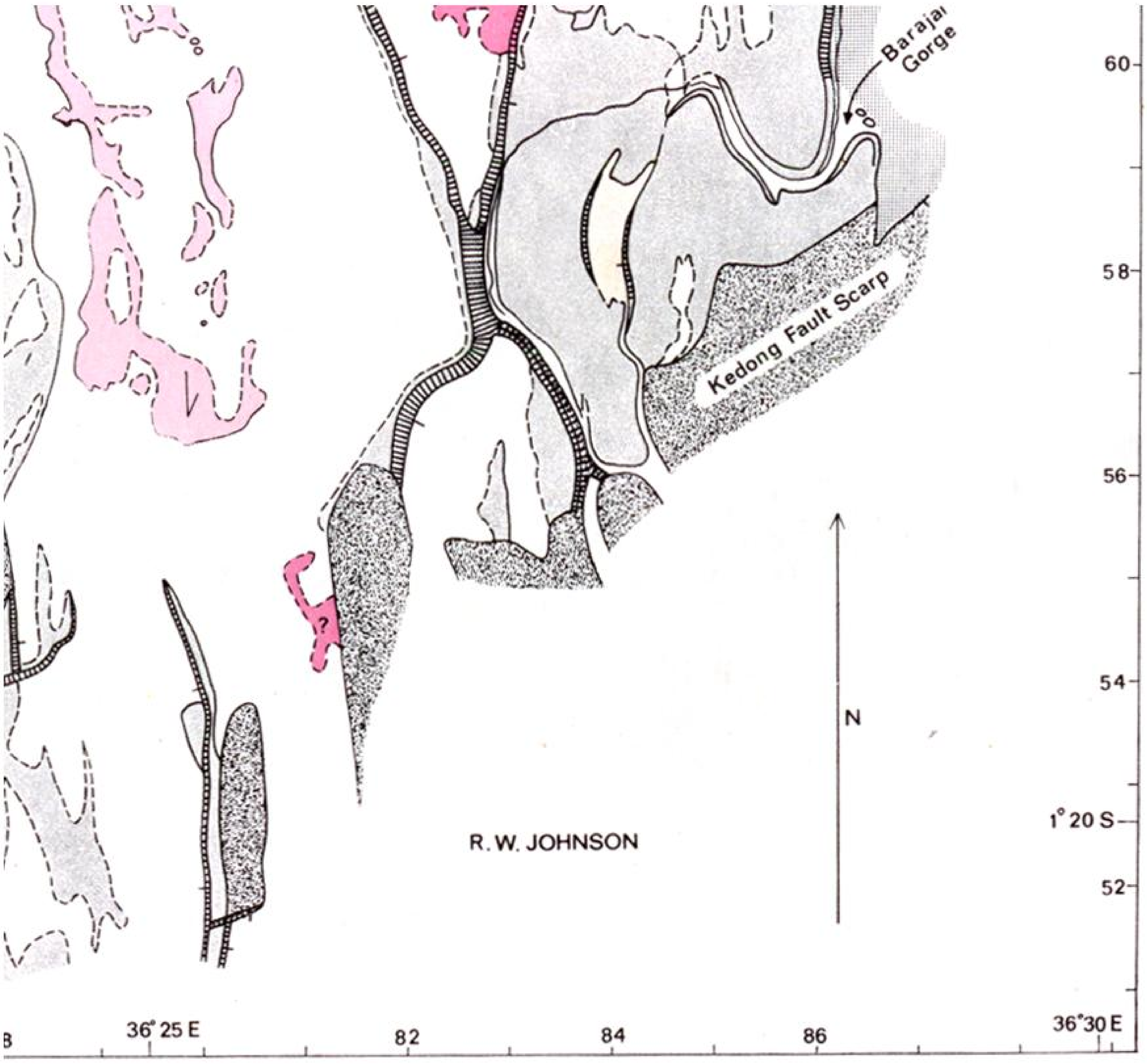

RING GRABEN COLLAPSE
Ol Doinyo Nyukie lavas & basal pyroclastic horizon
porphyritic &
non-porphyritic lavas
ring-feeder lavas &
pumice
CAULDRON COLLAPSE
pyroclastic horizon (lahars & accretionary lapilli tuffs)
sediments of Kedong Basin
lava flows with globule-surfaces (& globule flows)
lava flows lacking globule-surfaces
Plateau Trachyte Series flood lavas
older porphyritic flood lavas
54
1 20S
52
62
64
66
68
36°20E
72
74
76
78

Figure 16



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