On the Formation of Maars

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Summary

The Pleistocene maars in the Eifel region of Germany, and Massif Central in France, formed when fissures opened at the bottom of older valleys allowing stream water to pour down them and come into contact with rising magma. The resulting phreato-magmatic eruptions gave rise to both base surge and air-fall deposits. Spalling of wall rock at depth enlarged the fissure into an eruption chamber. Subsidence along a ring fault into the eruption chamber accounts for the larger crater cut into the country rocks. The volume relationship between the crater excavated, the ejected pyroclastic debris of the rim and the volume below the floor of the crater, indicates that the volume of the maar ejecta is always larger than the volume of the crater.

The relationships between maars and tuff-rings are described; the distinctive features of the two depend on density differences between the pyroclastic debris and country rocks, on the distribution ratio between ejected material and debris remaining within the underlying diatreme, and most importantly on the total amount of juvenile material produced.

Larger contents of juvenile material result in the formation of tuff-rings instead of maars, and in most cases also indicate a shallower eruption source of the former.

As a result of these many variables, large diatremes, which display subsidence structures bounded by ring-faults, may produce either maars or tuff-rings at the surface.

Introduction

During the last twenty years maars have attracted great interest (CIPA, 1956; FISHER and WATERS, 1969, 1970; FRECHEN, 1962; HEIKEN, 1971; ILLIES, 1959; JAHNS, 1959; LORENZ, 1970, 1971; MÜLLER and VEYL, 1956; NOLL, 1967; OLLIER, 1967; PETERSON and GROH, 1961, 1963; RAHM, 1956, 1958; REEVES and DE HON, 1965; WATERS and FISHER, 1970, 1971). As a result of recent investigations of base surge deposits associated with maars and tuff-rings (HEIKEN, 1971; FISHER and WATERS, 1969, 1970; MOORE, *et al.*, 1966; MOORE, 1967) it is now generally accepted that many maars and tuff-rings were formed when magma contacted ground water or surface water. This is believed to give rise to phreatomagmatic eruptions which produce pyroclastic fall-out and flow (base surge) deposits.

The large size of maar craters (up to 2 km) has been explained as indicative of either 'shallow explosions' — comparable to shallow nuclear explosions — (FISHER and WATERS, 1970), or subsidence caused by withdrawal of support (FRECHEN, 1962; JAHNS, 1959; NOLL, 1967).

The author's investigation of numerous maars, tuff-rings and diatremes in Europe and the USA suggests that a specific process controls the formation of most if not all of these structures. In this paper only a general account will be given of these processes, as a more detailed report is under preparation.

Because of the critical importance of terms used extensively in this paper the more important ones are explained below.

Maar: A large volcanic crater cut into country rock below general ground and possessing a low rim composed of pyroclastic debris (tuff or lapilli-tuff). Approx. 100 m to 2000 m wide; approx. several 10 m to more than 200 m deep; height of rim above general ground may reach a few m to nearly 100 m.

Tuff-ring: A large volcanic crater above general ground surrounded by a ring-like rim of pyroclastic debris (tuff or lapilli-tuff); in size similar to maars.

Diatreme: A pipe-like volcanic conduit filled with pyroclastic debris (tuff or lapilli-tuff) and blocks of wall-rock (see also LORENZ, *et al.*, 1970).

Phreatomagmatic eruption: Eruption caused by contact between ground water or surface water and magma. The gas phase is mainly steam derived from ground or surface water.

Base surge: A basal cloud spreading radially outwards from a crater as a density flow. Base surges are frequently associated with phreatomagmatic eruptions.

The Boos Maars, Eifel (Germany)

The Boos maars will be described briefly as they offer a striking example of the most important phenomena associated with maars in general. The two maars are associated with a number of other volcanic features and the whole system will be considered systematically from East to West. Figure 1 shows the distribution of the various volcanic manifestations, the stream, the sides of the valley and the adjacent (Nitzbach) valley.

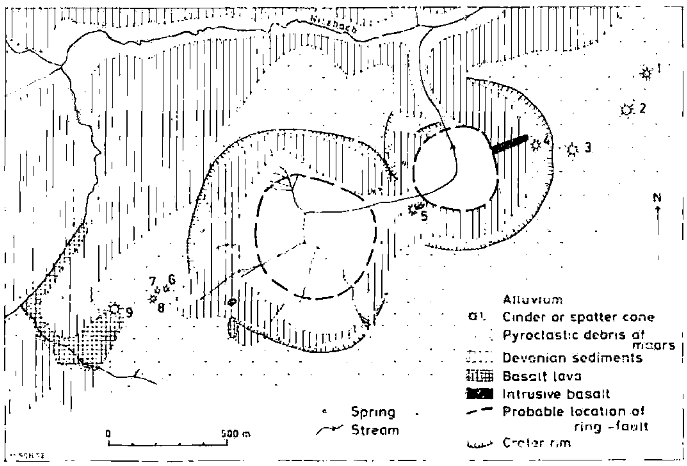

FIG. 1 - Geological map of the Boos fissure system, Eifel, Germany.

To the E and NE there are four cinder cones on top of the hill (Schneeberg). At the E slope of the E maar a 4-7 m wide alkali-basaltic dyke trends ENE. The two maars, cut into folded Lower Devonian slates, sandstones, and greywackes, are located at the bottom of the valley which today contains a small stream. The maars are 650-700 m in diameter and their depths below the local level of the country rocks are 30-87 m. Between the maars a small spatter cone and a lava flow were formed on the lower slope, but not in the bottom, of the valley connecting the maars. To the SW of the W maar (on the upper slopes of the valley) there are a basaltic plug (30-40 m in diameter) and a small lava flow, and four more cinder cones, the westernmost one of which also fed a lava flow which flowed into the adjacent Nitzbach valley (Fig. 1).

Detailed mapping of the ejecta indicates that cinder cones 1-4 (Fig. 1) were active before the E maar erupted. Cinder cone 1 continued to erupt after the E maar started its activity as it contains interbedded maar ejecta; cinder cone 3 was still hot as is indicated where maar ejecta bury cinders and spatter of the cone, but are only reddened and contact-metamorphosed where they overlie red spatter that became oxidized at high temperature (BAUDRY and CAMUS, 1970).

Close to the end of the E maar's activity the W maar started erupting. Deposits of this latter not only overlie the ejecta of the

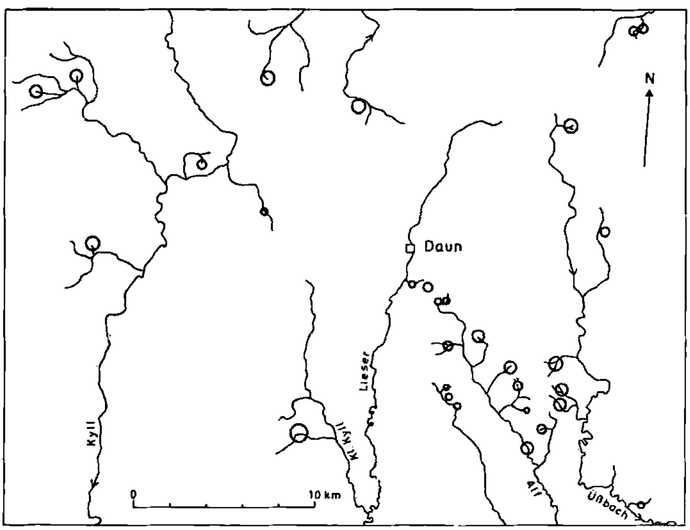

FIG. 2 - Relationship between maars and valleys in the Eifel, Germany (valleys that are not of interest in this respect are omitted).

E maar, but also cinder cones 8 and 9, and the lava flows from the plug and cone 9 (Fig. 1). At cone 8 a small spatter cone formed after the W maar had ceased erupting. Cones 6 and 7 were also active after the W maar ceased activity.

The location of the maars, cinder and spatter cones, plug, lava flows and dyke, and their complex field relations, especially those of the ejecta, clearly indicate that the features formed on an *en échelon* fissure system and were active practically contemporaneously. When a fissure opened on the valley slopes or on the tops of ridges, a 'normal' cinder cone, sometimes with an associated lava flow, formed. When the fissure opened at the bottom of the valley, however, a maar was formed. One fissure even opened on the lower slopes, but not actually in the very bottom, of the valley connecting the maars and a spatter cone was formed — not a third maar.

In this example, typical in many respects of other maars and related volcanic features in the Eifel, the maars thus represent a very localized volcanic phenomenon.

Maars in the Eifel (Germany) and Massif Central (France)

All but one of the 29 Pleistocene maars in the Eifel are, like the Boos maars, located in older valleys (Fig. 2), and cut into Devonian sediments, known to contain very little ground water (NOLL in OLLIER, 1967). Cinder and spatter cones are found on the valley slopes or on hills. Other examples of maars and associated cinder and spatter cones of the Eifel arranged on *en échelon* fissure systems are the Bad Bertrich fissure system, the Mosenberg-Meerfeld system, the Walsdorf system and the Sprink system (Fig. 3).

All but one of the 20 maars in the Massif Central in France are also located in older stream valleys (Fig. 4).

Features of the Ejected Material

When the Boos system is considered it is seen that the whole fissure system was active virtually contemporaneously, and the question naturally arises: « Why does the same magma give rise to a cinder cone at one locality and to a maar at another? ». An exceptionally high gas content of the magma causing the maar eruptions, as assumed by FRECHEN (1951), has to be excluded as only a moderate gas content is indicated by the associated cinder cones and lava flows, and even at the locality of the spatter cone (5 in Fig. 1) between the maars.

The exact coincidence of the maars with the valley floor suggests that stream water entering from above, or ground water circulating along joints or faults below the valley floor, provided the source foı the large amounts of gas required to eject the juvenile rocks and wall-rock debris.

The cinders and spatter of the cones of the Boos system are highly vesicular, black, or red where oxidised at high temperature, and comparable in all respects to cones in localities not associated with maars. Very few country rock fragments are associated with them indicating feeders of small width.

The maar ejecta, in contrast, contain very large amounts of country rock debris, up to 60-80 % or even more. The juvenile fraction is, in general, less vesicular, and therefore somewhat denser, than the cinders. In some cases juvenile material occurs as rather dense bombs, with what NAKAMURA and KRÄMER (1970) described as « par-

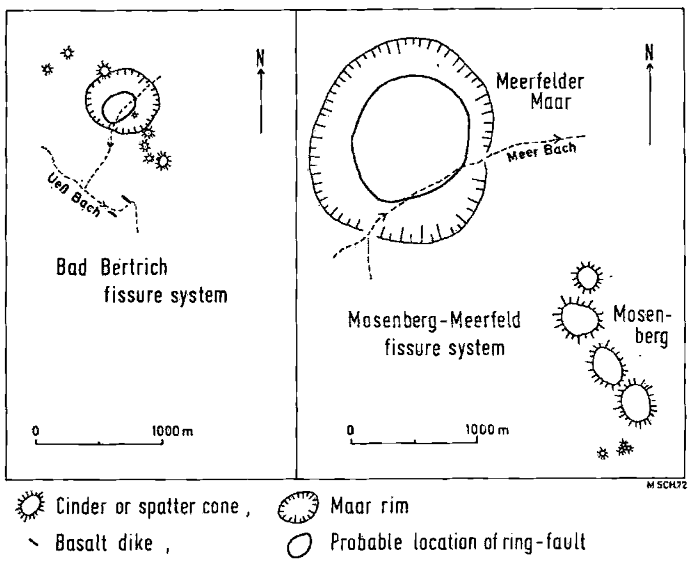

FIG. 3 - Fissure systems of Bad Bertrich and Mosenberg-Meerfeld Eifel, Germany (basalt lavas omitted).

ticulate structure » [1]. SCHMINKE (pers. comm.) suggested, on a joint field trip with the author in 1971, the term « cauliflower bomb » which describes the surface pattern and overall shape (if not the colour) of the bombs extremely accurately. These bombs typically contain many fragments of thermally altered Devonian country rocks.

In the maars of the Boos system, and elsewhere in the Eifel and Massif Central, the pyroclastic maar deposits are fine- to coarse-

(1) Particulate structure (NAKAMURA and KRÄMER, 1970): « The scoria is broken up locally (around the rim and in wedges) into subangular fragments, but these fragments are weakly to firmly welded together ».

grained, poorly to well bedded with units ranging from 1 to 40 cm in thickness. In 1970 NAKAMURA and KRÄMER published a brief account of base surge deposits in a quarry close to the Daun maars. Base surge deposits, however, occur at all the Eifel maars wherever good outcrops can be investigated. These are identified by:

— channels
— dune and anti-dune bedding
— blocks or bombs without impact structures in the underlying beds
— imbrication of Devonian fragments
— flow-orientation of elongated fragments
— diminishing of grain-size towards the margin of channels and above obstacles
— thinning of beds above obstacles
— increase in grain-size in front or behind obstacles.

At a few maars vesiculated tuffs are found. Vesiculated tuffs (*e.g.*, near cone 8 of the Boos system — Fig. 1) are an additional and extremely useful indicator of base surge deposits rich in water (LORENZ, 1970, and 1974 in press). Vesiculated tuffs were also identified at the maars of Praclaux and La Sauvetat in the Massif Central. Cauliflower bombs are very common there too, and contain xenoliths of granite or gneiss.

Of interest too, at Boos, impact sags under a few blocks and bombs point to the occurrence of simultaneous air-fall deposits. Ejection velocities calculated from the ejection distances (LORENZ and STEINBERG, in preparation) of these blocks indicate relatively low erosive power of the eruption clouds (see also p. 191).

The restriction of the maars to valley bottoms together with the various phenomena of base surge deposits, the impact sags (FISHER and WATERS, 1969, 1970; LORENZ, 1970, and in press; WATERS and FISHER, 1970, 1971), and the « cauliflower bombs » (NAKAMURA and KRÄMER, 1970), provide substantial evidence that copious amounts of *non-juvenile* water are intimately related to the maar eruptions.

In the cases of both the Eifel and Massif Central it seems quite clear that stream water entered fissures where they opened in the bottoms of valleys causing the phreatomagmatic eruptions which produced the maars. It is quite likely, though not essential to the hypothesis, that during the Pleistocene much more water than now was flowing down the streams. At the two maars (Weinfelder maar, Eifel, and Lac du Bouchet, Massif Central) which are not located in valley bottoms, ground water probably had access to the rising magma, as was the case with the maars of Big Hole and Hole-in-the-Ground, in central Oregon (LORENZ, 1970, 1971).

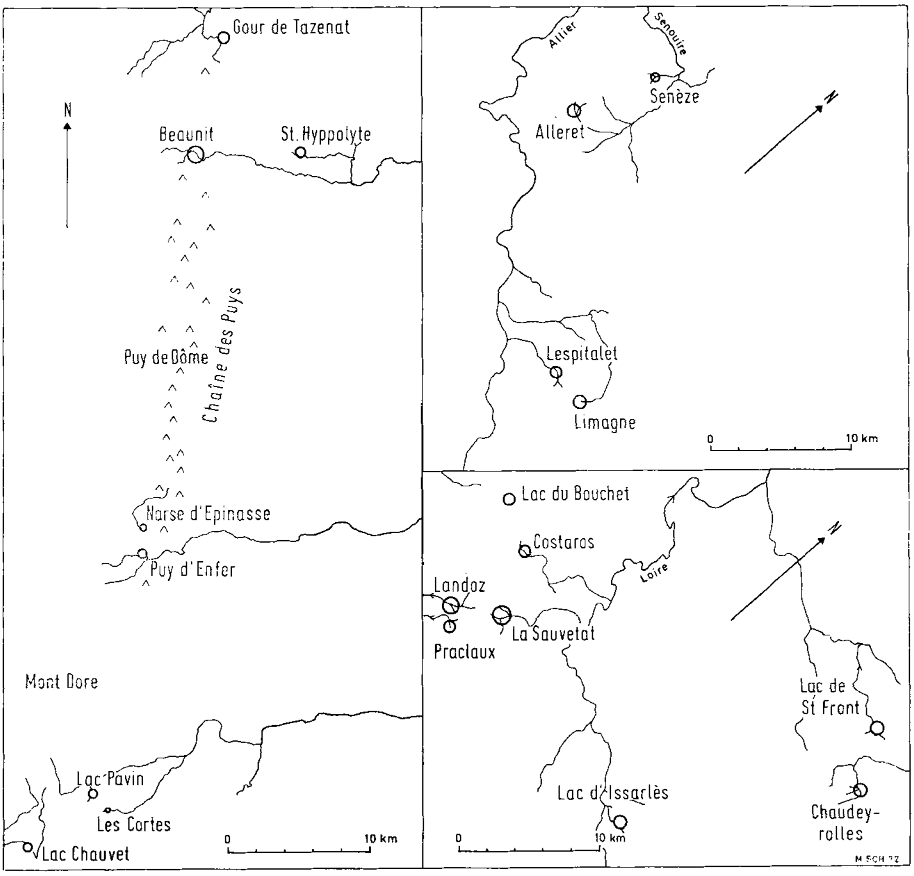

FIG. 4 - Relationship between maars and valleys of the Massif Central, France (valleys that are not of interest in this respect are omitted).

A striking example of a maar-forming historic phreatomagmatic eruption is that of Nilahue, Chile, described by MÜLLER and VEYL (1956) and ILLIES (1959). The vent opened in the valley of the Nilahue River creating a moderately sized crater. During periods of quiescence the valley's small stream formed a lake in this crater. Water must therefore have poured down the fissure, contacted the rising magma, undergone heating at the interface until it flashed into steam initiating an eruption.

As long as the tuff-ring crater of Surtur II, Surtsey, was not closed completely at sea-level, phreatomagmatic eruptions occurred (THORARINSSON, 1967). Only when the crater-wall was complete at sea-level was magma actually extruded as lava flows at the surface. This again clearly indicates the role of water: When sea water had access to the vent from above, eruptions were highly explosive, when the crater wall was closed, and no water could pour down the vent from the surface, eruption allowed extrusion of lava.

The nature of the pyroclastic deposits and positions of the maars clearly show that stream water must be considered capable of causing the phreatomagmatic eruptions which led to the formation of the maars in the Eifel and Massif Central.

Origin of the Craters

In most outcrops of the ejecta of the maar rims in the Eifel, the Massif Central and the USA, bedded units are generally successively deposited without evidence of erosion. The rather rarely observed channels, however, are cut into earlier beds, to depths usually of less than 0.5 m, occasionally for 1-2 m. This points to a relatively low erosive power of the base surges at the rim edge. This relatively low erosive power would, therefore, appear to make it impossible for the eruption clouds to excavate, to any appreciable extent, the (virtually unfractured) much harder, solid rocks at near-surface and deeper levels in the vent. This is especially true of the Massif Central where the wall-rock consists of granite, gneiss or basalt.

What then is the mechanism by which the large number of fragments of country rock are ejected?

Ejection distances of air-fall blocks or bombs rarely exceed 2 km measured from the centre of the craters. When the ejection velocities are calculated it is easily recognized that the energy of the eruptions is not large enough to excavate hard wall-rocks to form large craters (LORENZ and STEINBERG, in preparation).

At a shallow nuclear explosion or a meteorite impact the energy available for mechanical processes is spent in a fraction of a second and the resulting craters are formed within a few seconds. On the other hand energy release at most maars and tuff-rings, with the possible exception of very small structures, represents a mupltiple event as is indicated by the many, rather fine-grained, 1-20 cm thick units exposed in the crater rims. This, and the scarcity of large blocks in many maar deposits, is indicative of a low energy expenditure per unit time and volume, are thus indicative of a « non-explosive » origin (*i.e.*, multiple eruptions rather than a single event).

So, another mechanism must be found to account for the size of the crater of maars. At the Eifel it has already been suggested that caldera-like subsidence produced the maar-craters, because in most maars the volume of the existing ejecta does not equal the volume of the crater (FRECHEN, 1951, 1962; NOLL, 1967). Evacuation of a magma chamber as a result of nearby, related eruptions, or the subterranean withdrawal of magma were arguments used to provide the space into which overlying country rocks collapsed (FRECHEN, 1962).

At the Boos and other maars it is difficult to advocate the existence of a conventionally envisaged central magma chamber because the maars and related cinder cones formed on an *en échelon* fissure system. Hole-in-the-Ground maar in central Oregon is located on a fissure too (LORENZ, 1971*a*). This apparent contradiction — caldera-like subsidence and fissures as the source of the magma — is solved when the eruption mechanism is taken into consideration.

Eruption Mechanism

When stream-water or ground water enters a newly forming fissure and contacts the magma rising in the fissure the water forms a column above the magma and becomes heated under essentially constant volume. As in a geysir, pressure increases until the water finally flashes into steam. The steam rises rapidly towards the surface ejecting chilled and fragmented juvenile rocks (usually sideromelane grains), country rock debris and water. At the end of each eruption the pressure at the eruption source decreases and becomes even lower than the surrounding lithostatic pressure. This leads to spalling of the wall-rocks as observed in mines. Owing to their low tensile strength the wall-rocks burst into the open fissure, thus leading to enlargement of the initial fissure (SHOEMAKER, *et al.*, 1962). The enlarged fissure again fills with water from above and magma from below. With time this repeated process gives rise to an « eruption chamber » the shape of which probably looks like the lower part of a kimberlite diatreme (see below). The eruption chamber represents a space of intermittently higher and lower pressure in comparison to the water-column and surrounding wall-rocks.

At a critical pressure difference and size and shape of the eruption chamber, the overlying wall-rocks become unstable. A ring-fault forms, and subsidence of the wall-rocks enclosed by the ring-fault and the overlying subaerially deposited, bedded pyroclastic debris commences and continues as long as the eruption chamber and vent are not closed and the subsided rocks are not totally compacted.

During subsidence the eruptions may continue as long as there is a continued supply of magma and water and good contact between them. Subsidence and slumping will also effectively close the vent, so that moderately high eruption pressures can be built up again (LORENZ, 1971*a*). If there is not enough water flowing into the structure, and magma is still rising, it may intrude the diatreme to form plugs, irregular dykes, ring-dykes in the ring-fault, sills and irregular bodies. At the surface a cinder cone may form, or even a lava lake. If water gains access again after a long period of quiescence, phreatomagmatic activity may continue. In the case of the magma intruding most of the eruptive chamber, subsidence will come to an end. If there is no further supply of magma, at the end of phreatomagmatic activity, however, subsidence along the ring-fault, with accompanying erosion and slumping of the rim deposits, will continue for a prolonged time until no further compaction can take place in the eruption chamber and the overying rocks. As a result of erosion and slumping the crater reaches a diameter approximately 1.5 to 2 times the diameter of the ring-fault.

An excellent example demonstrating this prolonged subsidence as a result of compaction is the maar of Senèze, in the Massif Central. The maar is Villefranchian in age and located in the valley of the ruisseau de Senèze. It is cut into gneisses, and on the SW and W rim hard pyroclastic debris occur as small erosion relics. A ring-fault can be mapped nearly all round the crater floor, separating the gneiss of the wall from the bedded pyroclastic debris of the crater floor (Fig. 5). The pyroclastic debris is well exposed in several small outcrops and is world famous for its content of fossil vertebrates, including large mammals (DEVIS, 1969; BOUT, 1970; SCHAUB, 1944). The fossils and large fragments of bedded, hard lapilli-tuff from the rim point to their origin as re-deposited tuffs; this theory is also supported by the fact that these tuffs contain layers of diatomite and fossil fish, indicative of a crater lake. The pyroclastic beds of the crater floor thus represent debris derived from the crater rim, which, as a result of erosion and slumping, were deposited in the crater lake. Investigation of a 175 m deep drill hole shows that all the pyroclastic debris, penetrated down to that depth, represents lake deposits (DEVIS, 1969), and consequently was deposited after the eruptions had ceased. EHRLICH (1968) studied the diatomites of

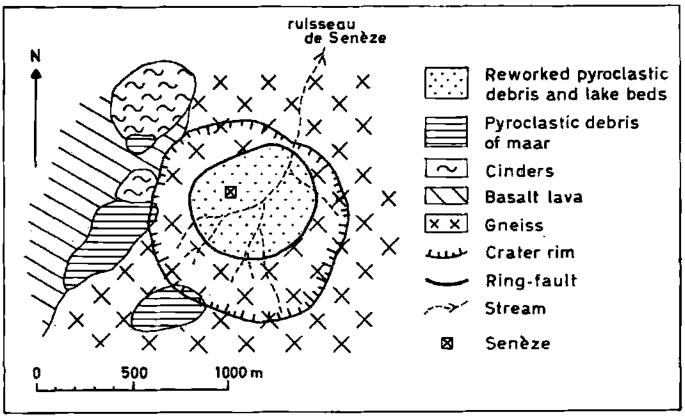

FIG. 5 - Geological map of the maar of Senèze, Massif Central, France.

the core and pointed out that at various levels the diatomites indicate rapid or slow deepening of the lake presumably as a result of subsidence of the crater floor. EHRLICH's interpretation was questioned by DEVIS who thought that filling of the crater with debris should be incompatible with sudden or slow deepening of the lake. Since the ring-fault was not known at the time of these studies, deepening of the lake was in fact difficult to interpret. Prolonged subsidence along the ring-fault, however, easily explains the results of the diatomite studies.

Volume Relationship

FRECHEN (1951, 1962) believed the general scarcity of tuffs at the rims of the Eifel maars to be largely an original one, and explained the present distribution of tuffs mostly by inclined directed blasts. Base surges, however, tend to flow towards depressions and thus can be assumed to have deposited their pyroclastic load mostly in the valley in which the maar formed and in adjacent ones. The unconsolidated deposits are easily eroded in the valleys, and this is probably the main reason for the scarcity of tuffs. Wind may also be an important influence, eroding tuffs on the hills. An additional factor that has to be considered is that many tuffs consist largely of comminuted Devonian sediments, and will form part of the present soil, especially where they originated as widespread, relatively thin layers. Finally the age of the maars indicated by FRECHEN (1951, 1962) may be too young since the samples taken for pollen and C^{14} determinations were mostly derived from the topmost layers of the crater floors. These layers, however, probably represent only the youngest sediments within the subsidence structure, deposited towards the end of the prolonged subsidence resulting from final compaction, and are not taken from the first lake deposits formed immediately after the cessation of eruptions. The time allowed for erosion therefore may have been longer than was originally assumed.

Since the maars of the Eifel and the Massif Central formed in older valleys the volume of that part of the valley cut by the crater has to be substracted from the crater volume measured at the pre-eruption surface in order to calculate the volume of the original wall-rock material removed through eruptive processes. In addition to the infilling from the crater rim the inflowing streams at many craters would have deposited part of their load in the subsiding structure, and when leaving the maars would also have removed a certain amount. It will therefore be very difficult to derive a good estimate of the original crater volume, and, as it is indicated above, of the original volume of the rim deposits by studying their present volumes.

If the maars formed above fissures, as the data given above indicate, the volume relationship between the maar crater and the ejecta can be calculated, in general, by applying a formula originally derived for the analysis of the Hole-in-the-Ground maar in Oregon (LORENZ, 1971*a*). The formula is based on the valid assumption that the total volume of pyroclastic debris, V_t, that takes part in the eruptions above and below the surface has to be larger than the volume of the original country rocks, V_w, of the space now occupied by the crater and the pyroclastic debris within the diatreme, because juvenile material, V_j, is added from the fissure:

$$V_t = V_w + V_j > V_w$$

The ejected volume, V_e, should then always be larger than the volume of the crater below the pre-eruption surface, V_c. The volume relationship is given by the formula:

$$V_d = \frac{V_e \cdot \rho_e (1 - \gamma) - V_c \cdot \rho_c}{\rho_c - \rho_d (1 - \gamma)}$$

Where V_d is the volume of pyroclastic debris within the diatreme (below the crater floor), ρ_e the density of the ejected debris, ρ_d the density of the debris remaining within the diatreme (vent debris and subsided pyroclastic debris), ρ_c the density of the country rocks and γ the fraction of juvenile material of the pyroclastic debris, assuming average densities and average distribution of the juvenile fraction within the total volume V_t. In this relationship only the pyroclastic debris is accounted for, the large blocks of subsided wall-rocks do not appear in this formula because they do not change their density. The total volume of the diatreme therefore is given by the formula:

$$V_p = \frac{(V_t - V_j) \cdot \rho_e + V_s \cdot \rho_c}{\rho_c}$$

where V_s is the volume of large blocks of country-rock, and assuming that the density of the pyroclastic debris is ρ_e.

At the Hole-in-the-Ground maar in Oregon, which formed on a fissure, the ejected volume is 0.125 km^3 and the volume of the crater 0.077 km^3, *i.e.*, only 61.5 % of the ejected volume. The densities ρ_e, ρ_c and ρ_d were assumed to be 2.0, 2.3 and 2.0 g/cm^3 respectively, and $\gamma = 0.1$, *i.e.*, only 10 % of the pyroclastic debris is of juvenile origin. The volume of pyroclastic debris within the diatreme is then 0.096 km^3, a value close to the one determined from the drilling results.

Owing to greater porosity and vesicularity the pyroclastic debris in general has a lower density than the country-rocks into which the structures are cut. Thus, the variation in the volume of the crater below the pre-eruption surface depends on the density differences, on the distribution ratio of the ejected pyroclastic debris to that remaining in the diatreme, and especially on the amount of juvenile fraction involved in the eruptions.

Above a certain percentage of juvenile material no crater cut into the pre-eruption surface will exist, instead a tuff-ring will form with a crater floor lying above the pre-eruption surface. At Hole-in-the-Ground no maar would exist had the juvenile contribution been 50 % of the total pyroclastic debris, if one assumes the same amount of country-rock involved and a similar distribution ratio of country-rock debris in the diatreme and ejected debris as in the existing structure.

Tuff-rings

Based on the evidence presented above, tuff-rings will, therefore, form when the magma water contact occurs at very shallow level, so that the effect of spalling is small and only comparatively small amounts of wall-rock material will participate in the eruptions. Subsidence along a ring-fault may still take place, however, but only along a ring-fault of relatively small diameter and minor displacement.

A tuff-ring may also form as a result of deep contact when magma continues contacting water for a long period of time after subsidence along a ring-fault has started. No new wall-rock material is then added from outside the ring-fault, and the marginal parts of the subsidence structure form a counter-current to the rising system in the vent during eruption. This is collar-subsidence (LORENZ, *et al.*, 1970), in which the whole system circulates, and with time more and more juvenile material is added diluting the amount of comminuted country-rock. The initial maar is thus slowly transformed into a tuff-ring.

The tuff-rings Hverfjall, Ludent, Hrossaborg, Surtur I and probably Surtur II in Iceland, studied by the author, and Fort Rock, central Oregon (HEIKEN, 1971), all provide evidence of a major unconformity. This unconformity is believed to be indicative of a ring-fault at depth associated with spalling and consequent subsidence into an eruption chamber. The beds unconformably overlying the older ones and draping over the rim edge into outward dipping layers clearly indicate that the eruptions continued after subsidence took place. At the tuff-ring Jolnir, associated with Surtsey, concentric faults due to subsidence, formed in May 1966. The eruptions, however, only ceased in August 1966 (THORARINSSON, 1968), pointing to the same process. Where there is no visible unconformity it is possible that an unconformity still exists, but is covered completely by younger beds.

At some maars some of the younger beds are even found dipping inwards (JAHNS, 1959), covering the near-surface slip-face that formed as a result of subsidence along the ring-fault buried below.

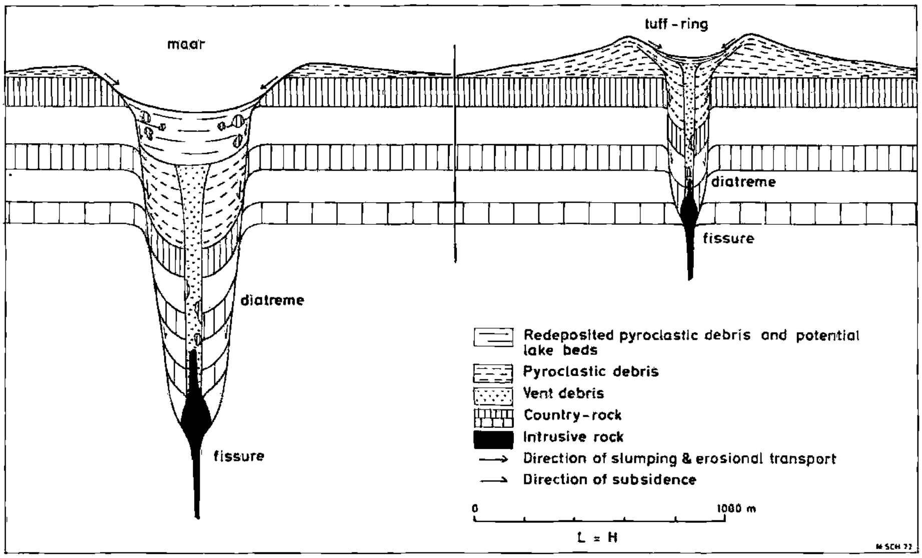

FIG. 6 - Schematic sections through maar-diatreme and tuff-ring-diatreme volcanoes.

At the tuff-rings mentioned above, and at the Menan Buttes in Idaho (HAMILTON and MYER, 1963), country-rock constitutes only from approximately 10 % to virtually none of the ejecta, which is probably indicative of a shallow eruption source. The juvenile fraction is highly vesicular, thus indicating shallow-level exsolution of juvenile gas prior to quenching, and hence a shallow-level for the magma/water contact. At the Icelandic tuff-rings there are also cauliflower bombs (see above), the presence of which is also indicative of the origin of tuff-rings by phreatomagmatic eruptions.

Diatremes

Studies of diatremes in Montana, USA (HEARN Jr., 1968), the Midland Valley of Scotland (FRANCIS, 1962, 1970; WHYTE, 1964, 1968) and the Palatinate, Germany (LORENZ, 1971 *b*, *c*) reveal the existence of subsidence structures bound by ring-faults, the diameters of which are of the same size range as the diameters of crater floors of maars and tuff-rings. Subaerially deposited, bedded lapilli-tuffs subsided on top of underlying country-rocks for several 100 m up to more than 1,000 m. This clearly indicates that their surface expressions must have been wide craters, largely formed through subsidence. Depending on the above given variables these craters must have appeared either as maars or tuff-rings, as already suggested by FRANCIS (1970).

A phreatomagmatic origin can be demonstrated clearly at the diatremes of the Palatinate and Scotland. The diatremes exposed on the coast of East Fife and East Lothian, Scotland, contain subsided base surge deposits, as indicated by foreset bedding with radial flow, flow deposited blocks and bombs, channels etc.

From a rather different point of view the diatremes of Montana are also very interesting. They are distributed within a broad zone, 160 km long, at both ends of which are partially brecciated dykes (HEARN Jr., 1968) suggesting that the diatremes themselves extend downwards into a dyke-swarm.

Kimberlite diatremes, which are of the same diameter range as other diatremes, are known to extend into dykes at depth (DAWSON, 1971). It is suggested here that the processes responsible for the formation of maars and tuff-rings as described above are probably also responsible for the formation of kimberlite diatremes. The floating reefs and concentrations of xenoliths at specific horizons (DAWSON, 1971) may represent remnants of country-rocks that subsided in a caldera-like fashion along ring-faults. If tuff-penetration and tuffisitization continue within a collapse structure, the bedding of the pyroclastic debris and the saucer-shaped structure, and the coherence of the subsided country rocks that underlay the subaerially deposited, bedded pyroclastic debris get destroyed, and large blocks consequently diminish in size. Continued activity may lead to thorough mixing of the components. In an extreme case no indication of caldera-collapse along a ring-fault would be left (LORENZ, 1971 *b*), and the original subsidence structure would appear as a large vent.

Chemistry

Since the contact of magma with water is the main reason why maars, tuff-rings and diatremes form, it is evident that the chemical composition of the contacted magma plays only a minor role.

The juvenile component is extremely variable. There are maars where it is tholeiitic (*e.g.*, Hole-in-the-Ground and Big Hole, Oregon), or alkali-basaltic (*e.g.*, Eifel, Massif Central). In some maars the magma is even carbonatitic in composition (*e.g.*, in Tanzania — DAWSON and POWELL, 1969), and there are a few maars where it was of intermediate or acid composition (*e.g.*, Lac de Pavin, Massif Central (CAMUS, pers. communication 1971). The same variation applies to tuff-rings and diatremes. In the Palatinate, Germany, the diatremes formed when magmas of tholeiitic, andesitic and dacitic composition contacted water (LORENZ, 1971 *b*, *c*).

Since the magmas are largely quenched, exsolution of juvenile gases is almost totally prevented, and only heat is transferred from the magma to the water and country-rocks. It is this heat therefore which is the force driving the whole process.

The scarcity of structures associated with intermediate and acid magmas is possibly the result of the smaller volumes of these particular magma types in relation to basic types; additional factors may be the amount of magma rising per unit time, the temperature of the magma, and the area of contact which to some extent depends on the mode of intrusion of the magma, acid magmas rarely rising along fissures at near surface level as basic magmas generally do.

A Proposed New Definition of a Maar, and Its Formation

During the last few years several new definitions of maars have been given (LORENZ, *et al.*, 1970; NOLL, 1967; OLLIER, 1967), all of which are deficient in some respects.

OLLIER's definition indicates that the ejecta consist of the material ejected from the crater, implying solely an « explosive » origin for the crater. He also states specifically that collapse plays only a minor role, a thesis subsequently questioned by FRANCIS (1970). NOLL writes that the craters are excavated by gas or steam eruptions, which seems to imply ejection of the material that originally occupied the space of the crater. He also points out, however, that subsidence plays an important role because the ejected volume does not match the crater volume. The volume discrepancy in the Eifel maars is now believed to be due to their advanced state of erosion. His distinction between maars *sensu stricto*, and subsidence basins, in respect of the Eifel maars — the latter having a greater diameter to depth ratio and showing a larger volume discrepancy than the former — therefore does not appear to be valid any longer, because erosion accounts for an increase in diameter to depth ratio to some extent.

The definition of LORENZ, *et al.* (1970) implies two possible modes of origin, one being mainly abrasion and slumping the other mainly collapse. Abrasion is active within all diatremes to a lesser extent, however, than was originally believed. Near surface slumping takes place at large maars as a result of subsidence along a ring-fault due to spalling at depth, and at very small maars it takes place as a result of spalling only. Since the formation of a slump plane and a ring-fault is the result of similar mechanical forces, there is a gradation between both and a distinction between the two end members does not seem too important.

Therefore a new definition seems to be required: A maar is a large volcanic crater cut into country-rock and possessing a low rim composed of pyroclastic debris. It is underlain by a correspondingly large diatreme. A maar forms when rising magma contacts ground-water or surface-derived water at a certain depth below the surface. The resulting phreatomagmatic eruptions give rise to base surge and air-fall deposits consisting of both juvenile and comminuted country-rock material. During quiet intervals spalling of wall-rocks leads to enlargement of the initial fissure and an eruption chamber is formed. Collapse along a ring-fault into this eruption chamber and consequent erosion and slumping at the surface accounts for the large crater at the surface. At a high ratio of juvenile to country-rock debris, collapse into the eruption chamber gives rise only to the wide crater of a tuff-ring. If the water supply diminishes the magma may intrude the diatreme and even reach the surface.

The large craters of maars are thus mainly formed through caldera-like subsidence as a result of phreatomagmatic eruptions.

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