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ScienceDirect
Journal of Volcanology and Geothermal Research 159 (2007) 285–312
Journal of volcanology and geothermal research
www.elsevier.com/locate/jvolgeores

Syn- and posteruptive hazards of maar–diatreme volcanoes

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Received 10 February 2005; accepted 23 February 2006
Available online 12 September 2006

Abstract

Maar–diatreme volcanoes represent the second most common volcano type on continents and islands. This study presents a first review of syn- and posteruptive volcanic and related hazards and intends to stimulate future research in this field. Maar–diatreme volcanoes are phreatomagmatic monogenetic volcanoes. They may erupt explosively for days to 15 years. Above the preeruptive surface a relatively flat tephra ring forms. Below the preeruptive surface the maar crater is incised because of formation and downward penetration of a cone-shaped diatreme and its root zone. During activity both the maar-crater and the diatreme grow in depth and diameter. Inside the diatreme, which may penetrate downwards for up to 2.5 km, fragmented country rocks and juvenile pyroclasts accumulate in primary pyroclastic deposits but to a large extent also as reworked deposits. Ejection of large volumes of country rocks results in a mass deficiency in the root zone of the diatreme and causes the diatreme fill to subside, thus the diatreme represents a kind of growing sinkhole. Due to the subsidence of the diatreme underneath, the maar-crater is a subsidence crater and also grows in depth and diameter with ongoing activity. As long as phreatomagmatic eruptions continue the tephra ring grows in thickness and outer slope angle.

Syneruptive hazards of maar–diatreme volcanoes are earthquakes, eruption clouds, tephra fall, base surges, ballistic blocks and bombs, lahars, volcanic gases, cutting of the growing maar crater into the preeruptive ground, formation of a tephra ring, fragmentation of country rocks, thus destruction of area and ground, changes in groundwater table, and potential renewal of eruptions. The main hazards mostly affect an area 3 to possibly 5 km in radius. Distal effects are comparable to those of small eruption clouds from polygenetic volcanoes. Syneruptive effects on infrastructure, people, animals, vegetation, agricultural land, and drainage are pointed out. Posteruptive hazards concern erosion and formation of lahars. Inside the crater a lake usually forms and diverse types of sediments accumulate in the crater. Volcanic gases may be released in the crater. Compaction and other diagenetic processes within the diatreme fill result in its subsidence. This posteruptive subsidence of the diatreme fill and thus crater floor is relatively large initially but will decrease with time. It may last millions of years. Various studies and monitoring are suggested for syn- and posteruptive activities of maar–diatreme volcanoes erupting in the future. The recently formed maar–diatreme volcanoes should be investigated repeatedly to understand more about their syneruptive behaviour and hazards and also their posteruptive topographic, limnic, and biologic evolution, and potential posteruptive hazards. For future maar–diatreme eruptions a hazard map with four principal hazard zones is suggested with the two innermost ones having a joint radius of up to 5 km. Areas that are potentially endangered by maar–diatreme eruptions in the future are pointed out.

Keywords: maar–diatreme volcanoes; syneruptive hazards; posteruptive hazards; hazard map

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doi:10.1016/j.jvolgeores.2006.02.015

1. Motivation

According to Wood (1980), Cas and Wright (1987), Wohletz and Heiken (1992), Vespermann and Schmincke (2000), and Schmincke (2004) maar volcanoes, next to scoria cones, represent the second most common volcano type on continents and islands. Since about 10% of the world population lives in areas of active volcanism (Baxter, 2000) hazards associated with the eruptions of the second most common volcano type deserve attention for human mitigation, volcanic emergency planning, especially community preparedness, evacuation planning and also medical preparedness — despite the fact that maar volcanoes are relatively small compared with the large active composite volcanoes.

Diverse hazards associated with the formation of maar–diatreme volcanoes are known from the many widely distributed studies on their eruptions and deposits. Since, however, no study has been oriented especially at these hazards exists, it is the purpose of this study to review and integrate the many presently known and diverse individual hazard aspects in one paper.

In hazard assessments, it is important to know the maximum and average effects of individual hazardous processes as well as of the sum effect of all hazardous processes. In the following chapters the maximum sizes of craters, tephra rings, diatremes, ejecta, and average and maximum heights and drift distances of eruption clouds and flow distances of base surges, velocities and ejection distances of ejecta, etc. known to this author are presented. This does not imply that these values are really the maximum values known and presented somewhere in the international volcanological literature. With this study it is not only the purpose to present in one publication a review of hazards related to these explosive volcanoes but also to stimulate more research in this field in order to get a better knowledge of the details of the potential hazards of this second most common volcano type in subaerial environments.

2. Introduction

Maars are volcanic craters up to 2–3 km wide and up to several hundred m deep (maximum size) when measured from the rim of the respective tephra ring. They cut into the preeruptive surface and thus usually expose preeruptive country rocks. At the level of the preeruptive surface maar craters may be in excess of 1 km in diameter. The craters are surrounded by a bedded tephra ring, which in cross-section on a horizontal preeruptive ground surface resembles a dune with a steep slope (30–35° immediately after the eruptions had ended) towards the crater interior and a relatively flat outer slope (5–15°). A preeruptive relief may, of coarse, affect the outer slope topography and angle. The radial width of a maar tephra ring may be 2–5 km when measured from the centre of the maar and depends on the size of the maar. The outer margin of the tephra ring depends on the thickness of tephra, which has not been decided upon yet because the tephra ring grades into the distal tephra deposits. At Hole-in-the-Ground, Oregon, the tephra isopach of 1 m reaches to a distance of about 2.5 km from the centre of the crater (which is 1.6 km in diameter at its rim) and the 0.5 m tephra isopach reaches to a distance of about 3 km (Lorenz, 1971a). The ejecta of maars contain a very high proportion of country rocks which may reach 80–90% of the tephra. Maars are underlain by a diatreme, which volumetrically is impressive, and thus the whole volcano is called a maar–diatreme volcano (Lorenz, 1975, 1985, 1986). They form by many individual phreatomagmatic explosive eruptions and associated collapse processes (Lorenz, 1973, 1985, 1986, 2000b, 2003a,b). Tuff-rings and tuff-cones are slightly different but genetically very similar volcanoes because they also form by phreatomagmatic explosive volcanism (e.g. Camus et al., 1981; Lorenz, 1985, 1986; Sohn, 1996, Sohn et al., 2003; Mattsson et al., 2006-this volume). Thus, despite the fact that tuff-rings and tuff-cones are not maars proper some aspects of known tuff-ring and tuff-cone eruptions will be discussed here.

In contrast to earlier models maar volcanoes are now almost only considered phreatomagmatic in origin and the phreatomagmatic equivalent of the intermediate, basic and ultrabasic scoria cones and of the intermediate to silicic pumice cones or domes (Ollier, 1967; Baudry and Camus, 1970; Lorenz, 1973; Ollier, 1974; Camus, 1975; Fisher and Schmincke, 1984; Lorenz, 1985, 1986; Cas and Wright, 1987; Brooker et al., 1993; Lorenz et al., 1994; Fisher et al., 1997; Schmincke, 2000; Lorenz et al., 2003; Schmincke, 2004).

Early studies were performed on the phreatomagmatic 1924 Kilauea eruption by Jaggar and Finch (1924), Stearns (1925), Stearns and Vaksvik (1935) as well as Jaggar (1949) and on the 1933 Pematang Bata eruption in Indonesia by Stehn (1934). Studies followed on the phreatomagmatic eruptions of the Nilahue/Carrán maar 1955 in Chile (Zuniga, 1956; Müller and Veyl, 1956; Illies, 1959), Iwo Jima 1957 on Volcano Island, Bonin Islands, Japan (Corwin and Foster, 1959; Fisher et al., 1997), Capelinhos 1957–1958, on Faial, Azores (Machado et al., 1962; Camus et al., 1981; Fisher et al., 1997; Cole et al., 2001), Surtsey 1963–1967, Iceland (Thorarinsson, 1964, 1966, 1967; Thorarinsson et al., 1964; Fisher et al., 1997), and Volcano Island 1965 in the Taal

Caldera, Philippines (Moore et al., 1966; Moore, 1967; Fisher et al., 1997), Walirang maar 1982, Gulunggung, Indonesia (Gourgaud et al., 1989), Miyake-jima 1983, Japan (Schmincke, 2000; Vespermann and Schmincke, 2000; Schmincke, 2004). Other historically erupted maars in monogenetic volcanic fields or on polygenetic volcanoes are listed by Noll (1967), Kienle et al. (1980) and White and Houghton (2000). In addition, many studies on Quaternary but also Tertiary maar, tuff-ring and tuff-cone volcanoes have been performed worldwide on the observed or deduced eruption activities, deposits, formation of craters, and the subterranean structure of maars and tuff-rings, i.e. the diatremes (e.g. Jahns, 1959; Einarsson, 1965; Reeves and De Hon, 1965; Noll, 1967; Ollier, 1967; Fisher and Waters, 1969, 1970; Baudry and Camus, 1970; Lorenz, 1970; Waters and Fisher, 1970, 1971; Heiken, 1971; Ollier, 1974; Camus, 1975; Schmincke, 1977; Kienle et al., 1978; Lorenz and Büchel, 1980; Kienle et al., 1980; Self et al., 1980; Wohletz and Sheridan, 1983; Büchel, 1984; Verwoerd and Chevallier, 1987; Di Vito et al., 1987; Sohn and Chough, 1989; Mastin, 1991; White, 1991; Sohn and Chough, 1992; Godchaux et al., 1992; Sohn and Chough, 1993; Büchel, 1993; Büchel and Lorenz, 1993; Ort et al., 1993; Mastrolorenzo, 1994; White, 1996; Sohn, 1996; Németh and Martin, 1999; Ort et al., 2000; White, 2000; Lorenz and Zimanowski, 2000; Sohn et al., 2003; Lorenz, 2004; White and Brand, 2004). Noll (1967) gave a valuable worldwide survey of maars and their respective references, and Ollier (1967) discussed what was known in his days about maars, their definition and genetic models.

Despite the fact that next to scoria cones maars represent the second most common volcano type on continents and island, in historic time the less common polygenetic volcanoes have erupted more frequently than both scoria cones and maars.

As stated above the intermediate to basic and ultrabasic magmatic equivalent of a maar–diatreme volcano is a scoria cone, with or without an associated lava flow or lava flow field, or very rarely also a small shield volcano of the scutulum type (Walker, 2000). The scoria cone studied best during its total life span is Parícutin in Mexico which erupted for 9 years (1943–1952) and reached a final height of 424 m (Luhr and Simkin, 1993; Fisher et al., 1997). In addition, it fed a lava flow field of 24.8 km^2. From 1759 to 1775, the scoria cone Jorullo erupted in the same region (Luhr and Simkin, 1993). It reached a final height of 350 m and its lavas covered an area of 1.25 km^2. Thus, despite different magma production rates, scoria cones may be active for more than 15 years. According to Luhr and Simkin (1993) most scoria cones are active for less than one year. Since most maar–diatremes are the phreatomagmatic equivalent of scoria cones and their associated lava flows, they may be active for an identical period of time, i.e. mostly for less than one year, but perhaps for a total of up to 15 years. At Parícutin, detailed observations of the growth of the scoria cone and its associated lava field allowed quantification of the magma production per unit time and its distinct decrease with ongoing activity. By analogy to this scoria cone, maars may also show a decrease in production rate during their period of eruptive activity.

Maar volcanoes have formed in all subaerial volcanic settings: in continental rift settings like the East African Rift Zone and the European Continental Rift Zone; in active continental volcanic and island arc settings; in foreland basins (molasse type) as, e.g. in the Hegau, southwest Germany, and in the Western Interior Seaway (Canada); in late orogenic intermontane basins of orogenic belts, as, e.g. the Variscan/Hercynian and the Caledonian orogenic belts; in basin and range settings as in the southwestern USA and in northern Mexico; on cratons with or without a platform sediment cover; on hot spot volcanic islands and continental hot spot tracks, as e.g. in the Ellendale–Noonkanbah volcanic fields, Western Australia, or in the Newer Volcanics Province in southeastern Australia.

In respect to the chemistry of the magmas involved in the formation of maar volcanoes the magmas in principle cover the full range of magmas involved in terrestrial volcanism: from rhyolite via dacite, latite, trachyte, phonolite, andesite, tholeiite, alkali basalt to nephelinite, leucitite, olivine melilitite, kimberlite, lamproite, even to carbonatite, to name only the more common magma types. The reason why the chemistry of the magmas including their variable content of dissolved volatiles and the exsolution of these volatiles do not play the main control on the characteristic mode of explosions of maar–diatreme volcanoes is that it is the heat of these magmas which on interaction of magma with groundwater is driving the explosions.

Whereas for most maars a phreatomagmatic origin is assumed (see, e.g. the volcanological textbooks of Williams and McBirney, 1970; Fisher and Schmincke, 1984; Cas and Wright, 1987; Wohletz and Heiken, 1992; Francis, 1996; Fisher et al., 1997; Schmincke, 2000, 2004) it has to be realized, however, that in respect to the formation of kimberlite and carbonatite maars and diatremes a controversy still exists between the models of phreatomagmatic formation (Lorenz, 1975, 1985, 1998a; Lorenz et al., 1994; Nixon, 1995; Kurszlaukis et al., 1998a,b; Lorenz et al., 1999a,b; Kurszlaukis and Lorenz, 2000; Kurszlaukis and Barnett, 2003; Mahotkin et al., 2003; Lorenz and Kurszlaukis, 2003, 2006-this volume) and predominantly magmatic formation of these maar–diatreme volcanoes (Clement, 1982; Clement and Reid, 1989; Stoppa, 1996; Kirkley et al., 1998; Stoppa and Principe, 1998; Field and Scott Smith, 1999; Scott Smith, 1999; Head and Wilson, 2003; Kjarsgaard, 2003; Lloyd and Stoppa, 2003; Wilson and Head, 2003; Webb et al., 2003; Hetman et al., 2004; Naidoo et al., 2004; Skinner and Marsh, 2004; Stiefenhofer and Farrow, 2004; Webb et al., 2004). Some of the above studies which predominantly favour a magmatic genesis also point out partial involvement of phreatomagmatic eruptions in respect to near-surface processes in kimberlite pipes, however, without going into detailed process-related reasoning.

3. Preeruptive precursor activities and hazards

Not very much is known about preeruptive hazards related to the formation of maar–diatreme volcanoes. If, however, most maar–diatremes are taken as the phreatomagmatic equivalent of scoria cones the preeruptive hazards of scoria cones can be taken as relevant for maar–diatremes.

Prior to the formation of maar–diatreme volcanoes or scoria cones, i.e. prior to the onset of either phreatomagmatic explosions respectively lava fountaining, rise of magma in a dyke-like fashion must have been facilitated by crustal extension. Thus breaking of rocks, forming new joints, joining and widening of pre-existing joints or faults by crustal extension and wedging aside of rocks by the rising magma result in release of fragmentation energy and consequent preeruptive earthquakes. If some earthquake foci migrate from greater depth towards the surface this would indicate rise of magma from depth upwards. Some release of magmatic gases at depth could possibly also result in some earthquake activity. Since these hazards are only related to crustal extension and rise of magma at depth below the initial level of maar formation they do not allow differentiation between imminent formation of a scoria cone and a maar–diatreme volcano. If the regional environment, however, had been conducive already in the past to the formation of maar–diatreme volcanoes, this preeruptive activity may be indicative of the potential of hazards of phreatomagmatic eruptions. Prior to the eruptions of the Carrán maar in the Nilahue valley several local earthquakes were felt (Müller and Veyl, 1956), respectively a moderate earthquake according to Illies (1959). Ten days prior to the opening of two craters at Pematang Bata a strong earthquake was felt in southern Sumatra and northern Java (Stehn, 1934). The Víti maar in the Krafla Caldera, northern Iceland, is said to have started erupting at about 9:00 on the 17 May 1724. During the previous night strong earthquakes were felt and during the eruptions additional earthquakes caused some houses to collapse in the nearby Myvatn area (Noll, 1967). These Víti maar eruptions started a period of lava effusions, the Myvatn Fires (1725–1729) (Noll, 1967), which represented a phase of crustal rifting previous to the one in 1975 to 1984 (Rymer et al., 1998). Judging from the more recent phase of rifting in northern Iceland it is not clear if the initial and later earthquakes in 1724 were really related to the maar eruption. It seems more probable that they were indicative of the start of crustal rifting in the Krafla area. In hazard studies related to potential future eruptions in the Auckland Volcanic Field within the city limits of Auckland, New Zealand, Chick et al. (2003) point out that “the warning period is likely to be short (due to low viscosity basaltic magma estimated to rise at speeds of around 5 km/h)”. On the other hand precursor seismic activity at Paricutin lasted for about 45 d and the earthquakes reached magnitudes up to about 4.5 (Luhr and Simkin, 1993).

An interesting question is what kind of seismic activity would arise from magma rising through widening joints already filled with groundwater at those depths where no explosive interaction between magma and groundwater is possible yet (see below).

In addition to earthquakes with a magnitude of possibly up to 4, at the surface release of juvenile gases (CO_2, CO, SO_2, H_2S, HCl, HF, etc.) and steam from evaporating groundwater may possibly occur.

4. Phreatomagmatic formation and concurrent growth of maar–diatreme volcanoes

Over the last 50 years the model of phreatomagmatic formation of maar–diatreme volcanoes has been formulated in increasing detail by a number of authors (Ollier, 1967; Fisher and Waters, 1969, 1970; Lorenz, 1970; Waters and Fisher, 1970, 1971; Heiken, 1971; Ollier, 1974; Schmincke, 1977; Wohletz, 1983; Wohletz and Sheridan, 1983; Wohletz and McQueen, 1984; Zimanowski, 1986; Zimanowski et al., 1986, 1997a,b; Wohletz, 1986; Godchaux et al., 1992; Büttner and Zimanowski, 1998; Zimanowski, 1998; Lorenz et al., 1994; Lorenz and Zimanowski, 2000; Schmincke, 2000; Wohletz, 2003; Lorenz and Kurszlaukis, 2003; Lorenz et al., 2003; Schmincke, 2004; Lorenz and Haneke, 2004; Lorenz, 2004; Lorenz and Kurszlaukis, 2006; Büttner et al., 2006). During the same time the model of phreatomagmatic formation of tuff-rings as well as tuff-cones has also been formulated in increasing detail (Hamilton and Myer, 1963; Thorarinsson, 1964; Thorarinsson et al., 1964; Einarsson, 1965; Thorarinsson, 1966, 1967; Heiken, 1971; Camus et al., 1981; Kokelaar, 1983; Kokelaar and Durant, 1983; Leys, 1983; Lorenz, 1985; Kokelaar, 1986; Lorenz, 1986; Sohn and Chough, 1989, 1992; Godchaux et al., 1992; Sohn and Chough, 1993; Sohn, 1996; Fisher et al., 1997; Sohn et al., 2003; Mattsson et al., 2006-this volume).

In brief, following the present model on phreatomagmatic formation of maar–diatreme volcanoes, maar–diatreme volcanoes form in subaerial environments when magma rises along a fissure and close to the Earth's surface interacts explosively with ground water. The magma, which has been in intimate contact with water, fragments into ash clasts (so-called interactive ash particles) of characteristic surface features (Büttner et al., 1999, 2002). A hydrostatic pressure barrier (term introduced in Lorenz, 1985, 1986) at low pressures (2–3 MPa) allows such thermohydraulic explosions to start only at shallow initial depth below preeruptive ground. Repeated explosions and thus eruptions cause "ejection" of groundwater by evaporation and in part possibly also by ejection of water droplets, the latter being real hydroclasts. Consequently the loss of groundwater at depth will have to lead, schematically, to a cone of depression at the eruptive fissure and in surrounding country rocks. By this repeated process explosions can occur and form explosion chambers at deeper and deeper levels, which collectively are called the root zone of the maar–diatreme volcano (Fig. 1). The country rocks affected by the explosions may either consist of hard rocks or they may be consisting of unconsolidated, i.e. soft rocks. Lorenz (2003b) and Lorenz and Haneke (2004) discussed the different hydrogeology in these two environments, its variation within the individual environments and its effects on the formation of maar–diatreme volcanoes.

Ejection of the fragmented (or unconsolidated) country rocks from the series of downward propagating explosion chambers causes increasing rock mechanical instability of the walls and roof of this root zone and the overlying rocks collapse into the partially evacuated root zone forming a cone of subsidence, the diatreme (Figs. 1 and 2). At the surface a crater has to form because the rocks underneath subside (see also Branney, 1995). This crater of subsidence origin is the maar crater. Because of lack of support, collapse of the country rocks of the free crater wall onto the crater floor results in a diameter of the crater at the preeruptive surface larger than the diameter of the diatreme at its upper end, i.e. at the floor of the crater (Figs. 1 and 2). As the crater in many areas gets incised into preeruptive topography, its crater walls can have varying heights and the crater rim (at the preeruptive surface) will be closer or farther away from the centre of the crater (Fig. 5). The ejecta from the eruption clouds form in the proximal (c. 1–3 km) area around the maar crater a relatively flat, bedded tephra ring, which radially extends into and thins towards the distal tephra deposits. This tephra ring represents the positive landform of the maar–diatreme volcano. Continued phreatomagmatic activity causes downward penetration of the root zone and repeated collapse and subsidence phases of the overlying diatreme and maar crater (Fig. 2). These collapse phases are responsible for growth of the diatreme and the maar crater in both diameter and depth. With ongoing phreatomagmatic activity the tephra ring surrounding the maar crater accumulates more tephra beds and, thus, it gets thicker. The collapse phases of the diatreme and the maar crater, however, also cause collapse of arcuate slices of the tephra ring overlying the preeruptive country rocks. As a consequence of the ongoing activity of the maar–diatreme volcano and repeated collapse of tephra slices the tephra ring migrates outward with time resembling a large concentric but radially, i.e. outwardly migrating and growing dune. Tephra from the "stoss side", i.e. from the crater wall of the tephra ring, gets repeatedly removed by collapse of arcuate slices onto the crater floor. Thus, in contrast to most other volcanoes which only build a positive landform, as, e.g. scoria cones, monogenetic domes, polygenetic shield volcanoes, and other composite volcanoes, maar–diatreme volcanoes in part penetrate downwards forming below the preeruptive surface a root zone, a diatreme, and a maar–crater, with the latter being a negative volcanic landform in the preeruptive surface. Details of these processes are discussed by Lorenz and Kurszlaukis (2006-this volume).

The smallest maar–diatreme volcano could result from one single eruption or from an eruption activity of only a few hours. The first explosion of Ukinrek West Maar at 4:00 a.m. AST on March 30, 1970, was observed unfortunately only from a distance of 65 km. Half a day later, at 17:00 AST, the crater was overflown by two pilots and was realized to be only 30–35 m in diameter. The next two days poor weather did not allow observation of the activity of West Maar (Kienle et al., 1980). However, at the end of its 3 d of activity West Maar had a diameter at its rim of 170 × 105 m and a depth of 35 m clearly implying growth of the crater during these three days of activity (Kienle et al., 1980; Lorenz, 1986; Büchel and Lorenz, 1993). Ukinrek East Maar erupted on the fourth day (April 2 AST, 1977) and was seen by an airline pilot at 11:00 (AST) to have a diameter of about 60 m. After 8 d of eruptions it reached a final diameter of 300 m and a depth of 70 m also

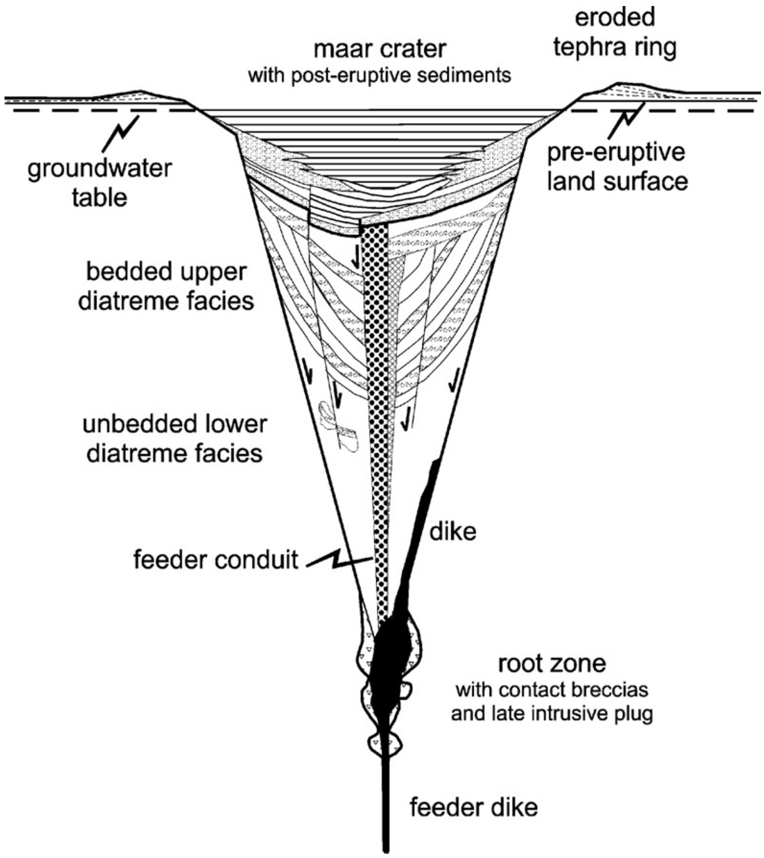

Fig. 1. Schematic diagram of an idealized maar–diatreme volcano with its feeder dyke, root zone, overlying diatreme, and maar crater as well as the tephra ring surrounding the maar crater. Note: the feeder dyke is out of scale (too thick). The bedded upper diatreme facies consists of alternating primary thinly bedded tephra and reworked thickly bedded tephra, i.e. lahar deposits. In posteruptive time the maar crater became filled with coarse sediments at its margins and finer grained lacustrine sediments in its centre. During syneruptive times subsidence of the diatreme fill caused formation of intra-diatreme faults which due to posteruptive compaction (in most diatremes) and diagenesis propagated upward (after Lorenz et al., 2003). Horizontal and vertical scale are roughly the same.

implying growth of the crater during the eruptive activity (Kienle et al., 1980; Büchel and Lorenz, 1993). The rhyolitic maar Víti in the Askja Caldera, Iceland is thought to have erupted for only about one day at the end of the Askja pumice eruptions in 1875. This maar, the eruptions of which were not observed from a close distance either, presently has a diameter of about 100 m and a depth of about 50 m (Einarsson, 1963; Sigurdsson and Sparks, 1978). The smallest Pleistocene maar in the West Eifel, the Hitsche maar, has a diameter of 60–70 m according to Noll (1967) and 100 m according to Büchel (1984). Probably the crater of the Pleistocene Hitsche maar was originally smaller, and posteruptively was enlarged by erosion. Judging from these data the phreatomagmatic eruptions can initially form a maar crater with a diameter as small as a few tens of meters (20–30 m) only and a depth of perhaps as small as 5 m. The root zone at the tip of such a small diatreme, assuming a cone-shaped diatreme with a wall angle of about 82° (Hawthorne, 1975; Clement, 1982; Lorenz, 1985, 1986) would have been at a depth of about 100 m. Very large maar craters have diameters in the range of 1.7 to nearly 3 km which they acquired only after a long period of activity. And if a diatreme is about 800 m in upper diameter, its lower end may reach a depth of about 2.5 km below the crater floor. The largest maar craters known in hard rocks could represent several maar craters, which intersected each other and thus coalesced. When large maars form in soft sediment environments the unconsolidated country rock sediments may allow formation of inner crater walls of rather low slope angles only (depending on country rock grain size and water saturation) and thus formation of very wide craters (Smith and Lorenz, 1989; Lorenz, 2003b).

The cone-shaped diatreme underlying a maar crater has a diameter at its top smaller than the diameter of the

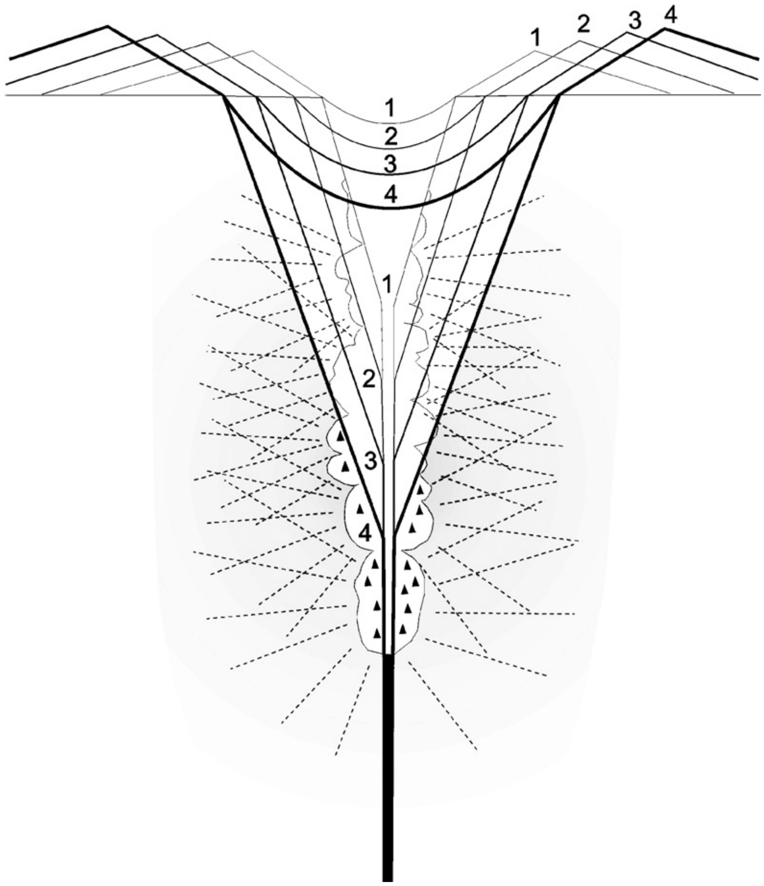

Fig. 2. Schematic diagram of growth of a maar–diatreme volcano showing 4 stages of growth (after Lorenz et al., 2003). The growth of maar–diatreme volcanoes lasts as long as the volcano is active and results from downward explosive penetration of the root zone on its own feeder dyke and consequent repeated collapse phases of overlying diatreme and maar crater — in this case 4 stages of collapse phases — during downward penetration of the root zone explosion chambers. The repeated collapse and thus growth of the diatreme causes engulfment of earlier parts of the root zone into the diatreme. Because of collapse phases of the (growing) maar crater arcuate slices of the tephra ring collapse onto the crater floor. The root zone and diatreme is surrounded by a halo of country rocks of lower density.

overlying maar crater at its rim. The reason why the maar crater is larger in its diameter at both the preeruptive surface and at the tephra ring crest is that maar crater walls collapse again and again easily because they are not stabilized by tephra as are, in contrast, the diatreme walls. The diatreme top diameter can only be as large as the diameter of the crater inside the line of the lowermost outcrops of undeformed country rocks in the lower crater wall along the crater floor. In hard rocks such a diatreme is assumed to have an angle of its cone-shaped walls on average of 75–85° towards the centre (Hawthorne, 1975; Clement, 1982; Lorenz, 1986; Clement and Reid, 1989). Judging from these diatreme wall angles the smallest diatremes could have an upper diameter of a few tens of m and extend to a depth of only about 100 m.

With ongoing eruptions the site of thermohydraulic explosions, the explosion chamber, penetrates downward. When several explosion chambers which collectively are called a root zone have formed next to each other and below each other, ejection of the fragmented country rocks leads to an increasing mass deficiency and consequent increase in rock mechanical instability of the country rocks surrounding and overlying the growing group of explosion chambers and finally to their collapse. Thus the overlying diatreme collapses and subsides repeatedly into the downward penetrating root zone and thus the diatreme itself penetrates downward and, similar to a sinkhole, grows both in depth and diameter (Fig. 2) (Lorenz, 1985, 1986, 2000a,b; Lorenz et al., 2003; Lorenz and Kurszlaukis, 2006-this volume). The largest diatremes may be in excess of 2000 m deep and have an upper diameter of about 800 to 1000 m. In soft sediments with their lower slope stabilities, the upper diameter may be larger. The Falkenstein diatreme in the Carboniferous–

Permian late Hercynian/Variscan intermontane Saar–Nahe Basin, Germany, formed during synsedimentary volcanism in unconsolidated water-saturated and thus soft rocks and has a maximum diameter of 1520 m (Lorenz, 1971b; Lorenz and Haneke, 2004). Its maar crater consequently would have been even larger, probably 2000–2500 m in diameter.

Repeated collapse and subsidence of the diatreme fill cause undercutting of the crater walls and thus cause collapse of unstabilized country rocks and overlying tephra from both the tephra ring and the tephra cover of the underlying crater wall country rocks. As a result rock falls and rock slumps of the country rocks result in collapse breccias, and the moist to wet tephra collapsing from the tephra wall and lower crater walls will form lahars (Lorenz, 1985, 1986; Lorenz et al., 2003). Dry tephra will form grain flows. With ongoing activity and increase in tephra ring thickness, radial growth of the diatreme has to slow down (Seyferth, 1996; Lorenz and Kurszlaukis, 2006-this volume). From a certain size onwards the maar crater will be large enough so that the eruption clouds can also deposit part of their load on the crater floor. With ongoing eruptions all these primary and reworked tephra and collapsed country rocks will subside inside the diatreme and will be overlain by younger deposits of the same diverse origin. Bedded tephra can subside within a large diatreme to depth of possibly 2500 m from the crater floor downwards because the diatreme represents a cone of subsidence (Hearn, 1968; Lorenz, 1985, 1986; Lorenz and Haneke, 2004; Lorenz and Kurszlaukis, 2006-this volume). Repeated eruptions through the conduits inside the diatreme will eject part of the subsided tephra again.

5. Syneruptive hazards due to eruptions of maar–diatreme volcanoes

5.1. Syneruptive earthquakes

Explosive interaction of magma and water, i.e. thermohydraulic explosions (Wohletz, 1983; Wohletz and McQueen, 1984; Zimanowski et al., 1991, 1995, 1997a,b; Büttner and Zimanowski, 1998; Zimanowski, 1998; Büttner et al., 1999; Morrissey et al., 2000; Büttner et al., 2002; Zimanowski et al., 1986, 2003), release shock waves which, similar to underground mining explosions, have the capacity to fragment large amounts of country rocks (Lorenz et al., 1999a; Lorenz and Zimanowski, 2000; Büttner et al., 2006). However, not very much is known about eruption-related earthquakes and their magnitude, or about acoustic waves which have been generated by maar-forming thermohydraulic explosions. The eruptions of the Riñinahue maar, Chile, are said to have been accompanied on the 4th and 7th of April, 1907, by strong local earthquakes (Illies, 1959).

Integration of results from seismic studies using large mining chamber explosions should allow evaluation of syneruptive earthquakes generated by phreatomagmatic explosions. In addition earthquakes generated by ongoing tectonic processes and the non-explosive magma rise resulting in the local explosive volcanism may also occur. The magmatic eruptions of Paricutin were accompanied by earthquakes in the Paricutin area of magnitudes up to 4.6 (Luhr and Simkin, 1993).

5.2. Eruption clouds

The eruption clouds rising within the conduit and leaving its vent on the floor of the maar crater consist of a mixture of juvenile and country rock clasts (and possibly water droplets) with a large variation in clast size. The clasts are supported and transported by expanding initially superheated steam generated from groundwater at depth, probably some small amounts of juvenile gases, and finally air mixed into and heated by the eruption cloud. After initial jetting and decoupling of the larger clasts these phreatomagmatic eruption clouds thermally rise regularly to heights of several km. Maximum heights of up to 20 km are known, as, at Nilahue/Carrán, Chile (Zuniga, 1956; Müller and Veyl, 1956; Illies, 1959), Volcano Island, Taal volcano, Philippines (Moore, 1967), Ukinrek, Alaska (Kienle et al., 1980), Walirang, Indonesia (Gourgaud et al., 1989), Grimsvötn, Iceland (GVP/USGS Weekly Volcanic Activity Report, 3–9. Nov., 2004). These heights are used by commercial air traffic, which consequently can be disturbed if it does not bypass the clouds. Atmospheric circulation (wind) causes these eruption clouds to drift to great distances. At Ukinrek, Alaska, some fine ash from West Maar drifted towards the E to distances of up to 160 km, covering an area of 20,000 to 25,000 km^2, and 5 d later fine ash from East Maar drifted N up to a distance of 90 km (Kienle et al., 1980). At Nilahue/Carrán eruption clouds drifted to distances in excess of 120 km, and at that distance deposited 1 mm of ash (Müller and Veyl, 1956; Illies, 1959). Today satellite images allow tracing of ash clouds to even larger distances. As a consequence, at Grimsvötn, Iceland, the subglacially generated phreatomagmatic eruption clouds in early November 2004 rose to heights of up to 12–14 km a.s.l. and via drift caused an area of 311,000 km^2 to be closed for air traffic (GVP/USGS Weekly Volcanic Activity Report, 3–9. Nov., 2004). The eruption clouds of Walirang maar in the crater of the composite Gulunggung volcano, Java, Indonesia, caused stalling of all four turbines, sandblasting of frontal parts of jets and emergency landings of two Boeing 747 jetliners in June and July 1982 (Gourgaud et al., 1989; Fisher et al., 1997). St. Elmo's fire due to static electricity was generated on the jet planes. At Nilahue/Carrán the eruption clouds rose to heights of 7000 m and are said to have caused almost total darkness over an area 20 km across (Müller and Veyl, 1956).

As a consequence of the generation of the eruption clouds air traffic has to be closed in the area affected by the drifting clouds.

5.3. Tephra fall

From the solid fraction of laterally drifting eruption clouds small lapilli and large and small ash grains may drift according to the velocity of the wind and the involved grain sizes to short or large distances. Fine ash from Ukinrek West Maar drifted within the eruption clouds to distances of up to 160 km (Kienle et al., 1980) and fine ash drifted from an eruption cloud of the Carrán maar, Chile, up to a distance of 120 km (Illies, 1959). Thus the lapilli and ash falling out of the drifting eruption clouds form the distal tephra blanket associated with the drifting eruption clouds. Drifting of eruption clouds because of specific wind directions causes, of course, the fine to median grained tephra to get deposited in wind-related sectors.

It has neither been established from field studies nor from experimental studies, but phreatomagmatic explosions in maar–diatreme volcanoes may also cause production of ash particles smaller than 7 µm, which are within the respirable size range of humans (<2 µm) and capable of entering the smallest air spaces of the lungs (Baxter, 1990). In case of acidic phreatomagmatic eruptions the possible occurrence of crystalline silica (cristobalite, trydimite and quartz) in the respirable size fraction has also to be taken in consideration (Baxter et al., 1998; Baxter, 2001).

Depending on the amount of water vapour contained in the eruption clouds and the atmospheric conditions the tephra may get deposited in rather dry, moist or even relatively wet conditions. Roads may get slippery, and car engines may be affected, thus surface transport corridors may have to be closed intermittently, and the volcanic activity may have an impact on nearby airports (Guffanti et al., 2003). Some roofs may collapse if the actual weight of the tephra is too high or when the syndepositional or postdepositional (rain) moisture increases its weight beyond the roofs' static stability. Destruction of vegetation on agricultural land is possible because of rain causing rapid induration of ash into a hard, concrete-like deposit. At the Carrán Maar, Chile, an agricultural area 7000 ha in area was damaged this way (Illies, 1959). Volcanic ash may severely interfere with fresh and waste water systems, not only during primary deposition but also during its removal (Brantley et al., 2003).

5.4. Base surges

Radial expansion and collapse of phreatomagmatic eruption clouds at maar–diatreme volcanoes regularly result in base surges which, over horizontal ground, will flow radially outward to in excess of 6 km (Moore, 1967: p. 348; Swanson and Christianson, 1973). Initial radial flow velocities of maar-related base surges may range from several tens of m/s (Moore et al., 1966; Moore, 1967; Valentine, 1998) to possibly in excess of 100 m/s. If the base surges are of rather high velocity (or get channelled by the relief) they can erode previously deposited tephra beds and form radial base surge channels (Moore, 1967; Lorenz, 1970; Heiken, 1971; Lorenz and Büchel, 1980). Because of the radial increase in area and condensation of superheated steam, the base surges rapidly lose kinetic energy and thus momentum. Consequently they decrease in velocity (to less than 15 m/s (Moore, 1967), ultimately to 0 m/s) and transport capacity and thus deposit their solid and water load downstream. Typical bed forms are of dune to antidune type to chute and pool structures, and of plane parallel bedding (e.g. Moore, 1967; Fisher and Waters, 1969, 1970; Waters and Fisher, 1971; Schmincke et al., 1973; Lorenz, 1974; Wohletz and Sheridan, 1979; Lorenz and Büchel, 1980; Sheridan and Wohletz, 1983; Walker, 1984; Lorenz, 1985; Wohletz, 1986; Dellino, 2000; Dellino and La Volpe, 2000).

Judging from their deposits in the tephra surrounding maar craters, most base surges deposit most of their load within 3 km (Walker, 1984), but more rarely as far as 6 km from the crater rim (Moore, 1967; Cas et al., 1993). Their run-out distance would be somewhat greater than maximum extent of preserved deposits. At Blue Lake maar, Mt. Gambier, South Australia, base surge deposits are exposed in road cuts up to 5 km southeast and east of the crater (Cas et al., 1993).

The base surge deposits form the tephra ring which surrounds the actual maar crater and may reach several tens to more than 100 m in height and from less than 1 km up to 5 km in radial distance from the centre of the crater — depending on the intensity of the eruptions, the length of the eruptions and influence of wind and topography. These base surge deposits account for most of the proximal deposits. Because of the many individual eruptions associated with the formation of a maar–diatreme volcano the tephra ring consists of several hundred to possibly several thousand individual base surge beds. The outer margin of the tephra ring reflects the run-out distance of most of these base surges. Since many of the eruption clouds are affected by either relief or wind or both, the associated base surges frequently also deposit their load in restricted radial sectors (Moore et al., 1966; Moore, 1967; Kienle et al., 1980; Ort et al., 1993, 2000; Bishop, 2000). At Ukinrek East Maar most of the individual beds of assumed base surge origin in the tephra ring only covered about one fifth to one third of the inner crater wall circumference, rarely more (Büchel and Lorenz, 1993). And also at Ukinrek East Maar a number of photographs showed that base surges clearly flowed beneath the respective eruption clouds, which drifted either towards the NW or SE in a very restricted radial sector (Kienle et al., 1980: Fig. 3). If a maar (or tuff-ring or tuff-cone) erupts in an area with pronounced relief the base surges are influenced by the local gradients and deflected from the radial directions (Moore et al., 1966; Moore, 1967). If a maar erupts in a valley, as happened frequently in the past, e.g. in the West Eifel Volcanic Field (Lorenz and Büchel, 1980; Lorenz, 1985, 1986; Lorenz and Zimanowski, 2000; Lorenz, 2003b), the base surges would in part be channelized by the valley and thus flow farther in the valley than in the surrounding hilly countryside. Consequently the sequence of base surge deposits would in all probability be thicker in this valley than on the neighbouring slopes, as at the Pulvermaar, Westeifel (Diele, 2000).

As the base surge deposits dominate volumetrically the tephra ring deposits, it is only outside the depositional area of the base surges that tephra fall from eruption clouds drifting away from the maar can form distinct accumulations comprising many individual thin beds. Outside the area of deposition from most base surges, i.e. laterally and beyond their run-out distance, tephra fall from the eruption clouds drifting overhead deposits ash and small lapilli on the tephra ring deposits and also outside the tephra ring and thus are responsible for the deposition of tephra in distal areas. A few features in the base surge deposits close to the rim or even on the inner slope of the tephra rings, such as accretionary lapilli, vesiculated tuffs, slump structures, and impact sags below blocks and bombs which impacted ballistically, indicate that the majority of the deposits were moist to wet. This implies that H_2O was deposited by the surges as water even close to the centre of the maar crater, although superheated water vapour may still have existed in some of the many base surges so close to source.

Fast base surges encountering trees and bushes near the maar crater uproot tree trunks or slice off the trunks above their roots or higher up and transport the tree trunks or fragments of trunks downstream, frequently orienting them parallel to the flow direction. At the Meerfeld Maar in the West Eifel such tree trunks up to 30 cm in diameter and up to several m long occur in a tephra pit c. 1.3 km away from the centre of the maar crater (Lorenz and Lutz, 2004). With decrease in flow velocity base surges can break off branches and twigs and erode the bark but the trunks may remain upright. During ongoing base surge activity tephra will accumulate around and embed the upright trunks (e.g. Lorenz, 1974; Lorenz and Büchel, 1980; Lorenz, 1984). Condensation allows wet ash, even vesiculated tuffs, to be plastered on the upright tree trunks and form wallpaper-like bedded deposits (e.g. Moore, 1967; Lorenz, 1974; Kienle et al., 1980; Lorenz and Büchel, 1980). Trees that collapsed underneath the initial tephra deposits, roots from the preeruptive soil, and wood fragments embedded in the tephra wall, during growth of the maar crater collapse onto the crater floor and might then get ejected and deposited higher up on the tephra ring by surges or even fall. At Ukinrek West Maar such wood fragments are found in the tephra beds of the tephra ring through two thirds of its total thickness (Büchel and Lorenz, 1993).

As is the case with the tephra fall deposits (see above) the smallest grain sizes produced in the thermohydraulic explosions and transported in the base surge clouds have not really been determined yet. Thus it is unknown if the finest particles of base surge clouds or deposits from intermittent eolian erosion of the base surge deposits represent a health hazard.

In the proximal area, i.e. the area of the tephra ring, there will be complete or partial destruction or burial (by more or less thick tephra) of settlements, individual houses, industries, roads, railway lines, bridges (transport corridors), and agricultural and forest areas as well as of transport lines/lifelines, i.e. high and low voltage power lines, telephone lines above ground up to a distance of several crater radii (radius at crater rim) mostly by the base surges and ballistically impacting blocks and bombs (see below) (e.g. Valentine, 1998). The damage will decrease radially outward because of decrease in dynamic pressure of base surges, decrease in thickness of tephra ring deposits, and decrease in number and possibly size of impacting blocks and bombs per area (see below).

Transport lines below preeruptive ground will mostly survive the load of the overlying tephra ring, but road repair work will be hampered or perhaps impossible where the tephra ring is too thick.

5.5. Ballistic blocks and bombs

As indicated above, thermohydraulic explosions result in the fragmentation of magma and hard country rock. As a consequence large amounts of country rock are ejected as fragments of various sizes during the eruptions. At the West Eifel maars, on average 20% of the ejecta consists of juvenile clasts (ash grains, juvenile lapilli, and also of bombs) and 80% of the ejecta consists of country rock clasts (Lorenz, 1985, 1986; Zimanowski, 1986, 1992; Lorenz and Zimanowski, 2000). When the large lapilli and blocks and bombs decouple from the eruption cloud soon after it has left its conduit and vent on the crater floor, with the larger clasts decoupling earlier than the smaller ones, they follow ballistic flight paths. They either fall ballistically onto the ground producing impact sags or during their ballistic fall they are swept away laterally by a base surge and deposited downstream without producing an impact sag. The depth of impact points to the large momentum of the respective clasts and the viscosity of the moist to wet tephra deposits (Lorenz, 1971a). Depending on their ejection angle and velocity (Steinberg, 1977; Steinberg and Babenko, 1978; Steinberg and Lorenz, 1983) the blocks and bombs impact at varying distances from the crater rim.

The size of the largest bombs ejected ballistically from (basic to ultrabasic) maars may reach 2 m (Mastin, pers. communication 2005) and depends partly on the effectiveness of magma fragmentation. A few cauliflower bombs at some West Eifel maars reach about 1 m in size, but at most Eifel maars the largest bombs are only a few tens of cm in size. The size of the largest ejected country rock blocks depends on the original joint pattern in the hard country rocks, i.e. on the distance of joints from each other and thus maximum size of originally internally unjointed blocks, on the introduction of such large blocks into the eruptive system, and on the transport capacity of the eruption clouds in the conduit.

Ballistic blocks up to 8 m (Fig. 3) and, in case of smaller blocks, maximum ejection velocities of up to 380 m/s (Steinberg and Babenko, 1978) (without considering reduced drag near the vent) were ejected from Hole-in-the-Ground maar in Central Oregon and produced impact sags in the underlying tephra beds. The larger blocks were derived from columnar jointed basaltic lava flows and ignimbrites in the country rock sequence penetrated by the growing maar–diatreme volcano (Lorenz, 1971a; Steinberg and Babenko, 1978). At the nearby Big Hole maar, the largest ballistically ejected blocks reached diameters of up to 2.3 m (Fig. 3) (Lorenz, 1970). At the Pinacate maars in Sonora, Mexico, the largest blocks ejected are 6 m across (Jahns, 1959; Wood, 1974), and at the Graenavatn maar, SW Iceland, which is only 340–260 m in diameter, the largest blocks ejected are 4 m in diameter (Noll, 1967; Lorenz, unpubl. data). The joint pattern of the Devonian country rocks of the West Eifel maars (shales, sandstones, slates, quartzites) apparently allowed maximum diameters of ejected blocks of only up to 2.5 m whereas some ejected country rock basalt blocks reached 4 m in size. Ejected blocks and large lapilli may reach maximum distances of 4 km as did lapilli 3–5 cm in diameter ejected from Hole-in-the-Ground maar in Central Oregon (Fig. 3) (Lorenz, 1971a; Fisher and Schmincke, 1984: Figs. 9–8). At the trachytic Lac Pavin maar in the Chaîne des Puys, Massif Central, France, the largest ejected blocks have a diameter of 4.5 m and were ejected to a distance of 700 m from the centre of the maar crater (own unpublished data).

It is important to realize that at some maars most of the ballistically ejected blocks follow a systematic decrease in diameter with distance (Fig. 3). This relationship indicates that the blocks of various sizes drifted in the eruption clouds (drift flow) at least in the upper part of the conduit and to some extent also in the lowermost levels of the eruption clouds. The larger the blocks the slower their ejection velocity, the smaller the blocks the higher their ejection velocity (Lorenz, 1971a). Owing to their greater mass to surface-area ratio, the larger blocks should decouple from the eruption cloud earlier than the small blocks and the lapilli. In contrast to block deposits which show a systematic lateral decrease in size, Self et al. (1980) describe from Ukinrek Êast Maar a different size distribution of initially ejected blocks. In this case the maximum ejection distance of small and large blocks is almost the same, with the larger blocks having been ejected to a slightly larger distance than the smaller ones. This distribution indicates that all blocks ejected at the vent had almost the same initial ejection velocity and because of lower effect of air drag on the larger blocks these could fly ballistically to a slightly larger maximum ejection distance than smaller blocks. Mastin (1991) describes a similar block distribution from the phreatic eruptions of the Inyo Craters. This same initial ejection velocity of blocks irrespective of their size implies plug flow (Lorenz, 1971a) in the conduit up to the vent on the crater floor and was also typical for explosions of some composite volcanoes as, e.g. Arenal, Mexico, and Asama, Japan (Minakami, 1942, 1950; Minakami et al., 1969). Close to the explosion focus, the initial post-explosion expansion phase (following the pressure gradient up the conduit) imparts almost the same velocity to all fragments irrespective of their size and leads to plug flow in the eruption conduit. If an explosion occurs

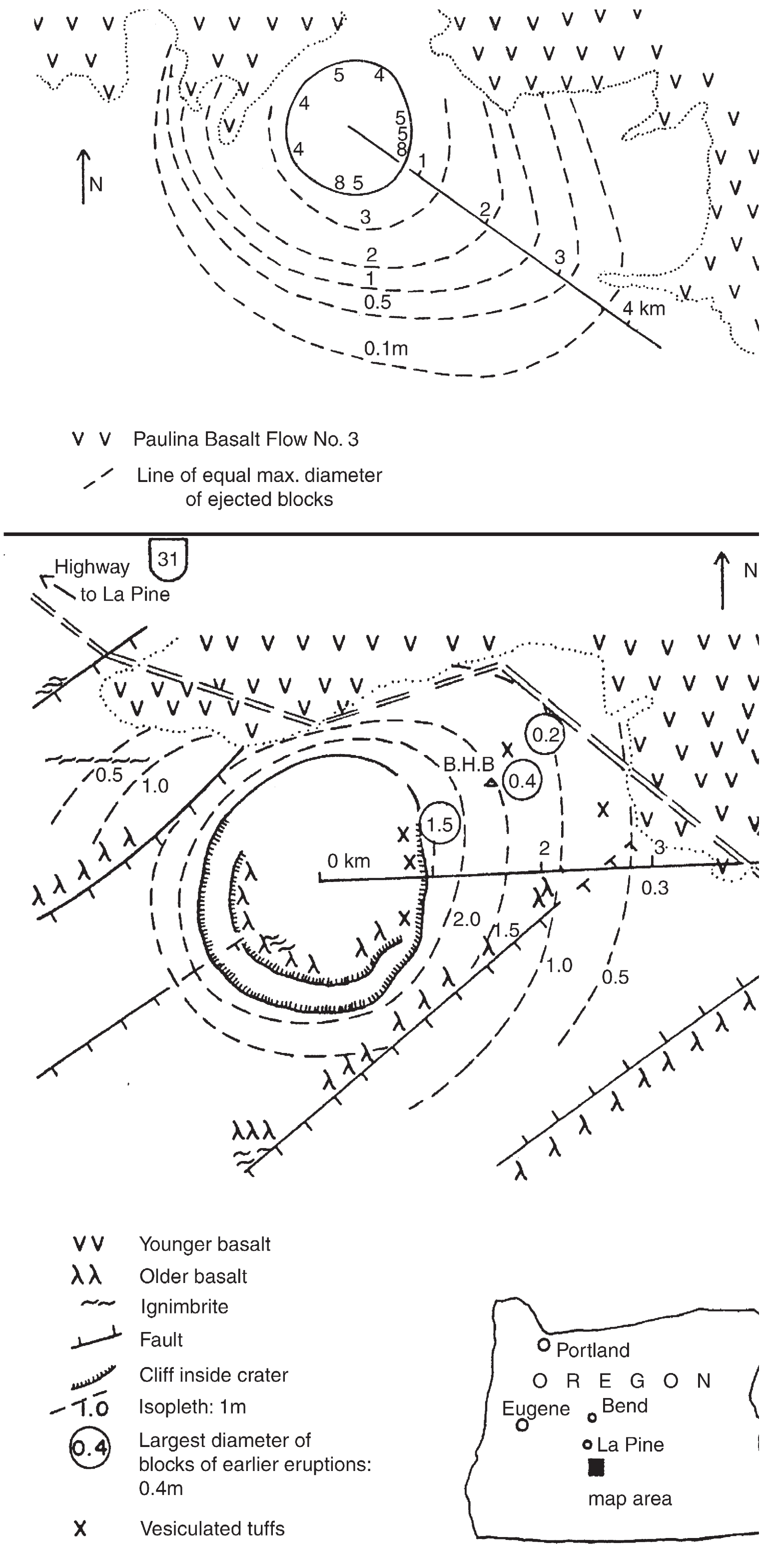

Fig. 3. Map showing isopleths of diverse maximum block sizes of blocks ejected from the two maars Hole-in-the-Ground and Big Hole, both in Central Oregon, USA (after Lorenz, 1970, 1971a).

rather close to the Earth's surface the ejecta should leave the vent almost under the same velocity. It is suggested here that if, however, an explosion occurs in the root zone of a deep diatreme this plug flow may change inside the long vertical conduit of the diatreme to drift flow. If change in the arrangement of the isopleths of ballistically ejected blocks during the volcanic activity of a maar–diatreme points to a change from plug flow to drift flow this change may also point to the downward penetration of the root zone explosion chambers during growth of the respective maar–diatreme volcano (see also Self et al., 1980).

As ballistic blocks and bombs usually do not reach very large distances they mostly impact on the tephra ring. And those ballistic blocks and bombs which despite following their trajectories get caught effectively by base surges and are swept downstream also get deposited mostly on the tephra ring. The largest blocks transported by base surges and known to this author in tephra rim deposits of maars in the West Eifel, Germany, and Massif Central, France, have diameters between 1 and 2 m and have been transported to distances of at least 1.5 km from the centre of the crater. Maximum transport distances of such blocks in both areas are not known because of lack of respective outcrops.

During the eruptions there is a variation in eruption parameters and thus the maximum size and maximum ejection velocities of blocks can vary. At Hole-in-the-Ground maar, Oregon, large blocks (up to 3–8 m in diameter) only occur in four distinct horizons with the last one near the top of the ejecta sequence (Lorenz, 1971a).

In the area of ballistic fall of blocks and bombs, which almost coincides with the area of the tephra ring, there can be partial or even complete destruction of some houses (roofs, walls), partial destruction of roads and transport lines/lifelines, e.g. high and low voltage power lines, and telephone lines above ground up to a distance of possibly 4–5 km. Agricultural and forested areas may also be affected to some extent. Because of their large momentum ballistic blocks, bombs and large lapilli can severely wound or kill people and animals (Baxter, 1990; Baxter and Gresham, 1997; Tanguy et al., 1998; Baxter, 2000). Hot juvenile clasts (bombs and large lapilli) may ignite dry organic material and thus start fires. This author does not know of historical examples of such damages and casualties from maar eruptions but analogous examples can be taken from recent historic eruptions of composite volcanoes from the literature (e.g. Baxter, 1990; Baxter and Gresham, 1997; Baxter, 2000; and references therein). Di Vito et al. (1987) describe the events of the 1538 Monte Nuovo tuff-ring eruption leading to 24 casualties.

Because of base surges and their sandblasting effects, ballistic block and bomb impacts, and thickening of tephra deposits in the tephra ring, i.e. during growth of this positive landform part of the erupting maar–diatreme volcano, the infrastructure above ground will be affected by both the dynamic processes (e.g. Valentine, 1998) and the increasing load of the tephra accumulating on the tephra ring. These effects will be most intensive the closer the objects (houses and other infrastructure objects) are to the centre of the crater and, because of radially outward decreasing effects of surges, impacting blocks and bombs, and load of deposits the effects will be less intensive.

5.6. Lahars

In an area of relief, as is common in many hard rock environments, deposition of moist or wet tephra on slopes in the near vicinity of a maar crater can lead syneruptively to the formation of lahars. Syneruptive rain or melting of snow might also induce formation of lahars. These lahars will follow the relief gradient and flow downslope into "suitable" lahar inundation areas (Vallance, 2000; Schilling and Iverson, 2003). In case of sufficient mass, lahars will flow into the valley within which a maar crater has formed or into nearby valleys. At the Hardt Maar near Bad Bertrich in the West Eifel lahars from the tephra ring and the neighbouring steep slopes flowed into the Ueβ valley the stream within which is approximately 200 m below but only 600 m away from the Hardt maar. These lahars flowed down the Ueβ valley for at least 1 km. Similar lahars flowed into neighbouring valleys at several maars in the Bas Vivarais Volcanic Field, Massif Central, France as, e.g. at the maars of Eschamps and St. Martial (G. Camus and A. de Goër, pers. commun. 1982, and own data). These lahars thus indicate that the moist to wet base surge deposits of the tephra ring provide a rather high potential for the formation of lahars where the tephra was deposited on steep topography.

Lahars, therefore, could partially or completely destroy houses, transport corridors and transport lines. Even people and animals could be affected by lahars in valleys some distance (up to a few km) away from an erupting maar if not evacuated early enough.

5.7. Other possible syneruptive erosion

As with tephra deposits of composite volcanoes, in case of strong rain in between or during the eruptions, newly deposited proximal to distal tephra may be flushed into nearby streams and rivers, result in congestion of the drainage system, formation of new channels, and get deposited downstream and in overbank areas. In addition it may also be deposited on other near-horizontal agricultural and rural areas as well as on roads and on fields. Ash flushed into fresh and waste water systems may damage these systems. Strong winds during and in between eruptions can erode the fine ash fraction of newly deposited tephra. This fine ash may also represent a hazard to people and animals, when inhaled, and possibly also to crops.

5.8. Release of juvenile gases

Depending on the chemistry of particular maar-forming magma a variety of juvenile volatiles (CO_2, CO, SO_2, H_2S, HCl, HF, Rn, etc.) may occur in eruption clouds and have hazardous effects (Baxter, 1990). Some of these gases may destroy or adhere to vegetation and crops. However, from historic phreatomagmatic maar eruptions it is unknown what kind of juvenile volatile species have been released from the magmas and distributed in the eruption clouds. It is also unknown if these juvenile gases had any negative effects on people, animals and vegetation.

5.9. Damming of lakes

If a maar–diatreme forms in a valley with an appreciable stream flow then this stream may be dammed (forming a lake upvalley) by the growing tephra ring, which will be thicker on the valley floor than on the surrounding valley slopes and surrounding hills. Downvalley, the stream will run dry for some distance because its original surface water supply will have been blocked and underground the local groundwater table will have subsided because of local formation of a cone of depression during the activity of the maar–diatreme volcano.

5.10. Reduction of surface and near-surface groundwater

Since the phreatomagmatic eruptions draw groundwater from the vicinity surface water may disappear locally and the groundwater table may subside locally by formation of a cone of depression. Lack of this surface water and subsidence of groundwater table may thus develop syneruptively and thus reduce available local surface- and ground-water supplies.

5.11. Variation of production rate during ongoing volcanic activity

During the activity of monogenetic volcanoes (scoria cones, tuff-cones and maars) the production rate frequently decreases with ongoing activity. Examples of such a decrease are the scoria cone Parícutin, Mexico, the phreatomagmatic tuff-cone complex Surtsey, Iceland and the Nilahue/Carrán maar in Chile (Illies, 1959; Thorarinsson et al., 1964, Thorarinsson, 1964, 1966, 1967; Luhr and Simkin, 1993). Thus, at many maars it may be the initial phase, which is be the most hazardous. Short and especially increasingly longer repose periods near the end of the eruptive activity may suggest, however, a false end to the eruptions and represent a hazard of its own (see also Section 7). At Hole-in-the-Ground, Oregon, however, one of the largest eruptions occurred close to the end of its eruptive activity (Lorenz, 1971a).

5.12. Injuries and trauma

As with other volcanic eruptions and other natural disasters, maar–diatreme eruptions may not only cause physical injuries to people only, but some people, especially the elderly ones and children, may be traumatized by the unexpected volcanicity and its effects on their lifestyle and consequently they need psychological help.

6. Syneruptive hazards due to growth of maar–diatreme volcanoes

During ongoing activity of maar–diatreme volcanoes the maar crater and the underlying diatreme both grow in depth and diameter (Lorenz, 1985, 1986, 2000a,b; Lorenz and Zimanowski, 2000; Lorenz et al., 2003; Mattsson et al., 2006-this volume; Lorenz and Kurszlaukis, 2006-this volume).

In case a maar–diatreme erupts in a populated and built-over area collapse of the maar crater will cause total destruction of settlements, houses, roads, railway lines, bridges, i.e. transport corridors, and agricultural and forested areas up to a distance of one crater radius (measured at the preeruptive surface). This hazard also affects all transport lines/life lines above preeruptive ground (i.e. high and low voltage power lines, transformer and mobile phone relay stations, telephone lines, water channels, and pipelines) existing in the area of formation of the crater. In addition all transport lines below preeruptive ground (i.e. electricity and telephone cables, gas, oil or other pipelines, and underground water and sewage systems) will be destroyed in the area of formation of the maar crater. After its initial formation the maar crater grows in diameter and depth by repeated collapse of inner segments of the country rocks in the crater wall below preeruptive ground and of overlying segments of the tephra ring. During growth of the maar crater all buildings and other installations above and below preeruptive ground will collapse onto the crater floor. As the diatreme evolves as a growing cone of subsidence, tephra, country rocks, reworked tephra (see also Houghton and Smith, 1993), and the debris of the above buildings and installations subside inside the diatreme down to depths of up to possibly 2500 m. Some of the fragmented materials can get further fragmented and even re-ejected by the ongoing eruptive activity and deposited either on the crater floor or on the bedded tephra ring. If toxic chemicals were stored in buildings destroyed by the growth of the maar crater these chemicals during rejection and incorporation in the eruption clouds may affect large areas outside the crater.

7. Hazard of potential renewal of eruptive phreatomagmatic activity at same site

After some days of inactivity of a maar crater the question will arise if the eruptions really have ended and if a return to safe conditions is indicated. According to Illies (1959) after 4 d (27–30 July 1955) of intensive eruptions of the Nilahue/Carrán maar in Chile the activity slowed down and weak intermittent individual eruptions followed until the end of August 1955. Di Vito et al. (1987) described the eruptive activity of Monte Nuovo, Campi Flegrei, Italy, which erupted for a week in 1538: “The first two days of the eruption were characterized by explosive behaviour, … and led to the growth of the main body of the cone around the vent. Four days of relative quiescence with only minor explosive activity followed. The eruption finally ended on 6 October, the seventh day, with a violent explosive phase and the emplacement of a small scoria flow. Twenty four people, who were climbing up to the vent during this last phase, were killed by a sudden explosion.” As long as the feeder dyke of a maar–diatreme volcano is not solid enough to prevent further rise of magma such a new rise of magma might cause new eruptions and then, in retrospection, the eruptive activity had obviously not come to an end. Thus, depending on the thickness of the feeder dyke, it may take weeks to possibly months to be certain that the eruptions have really ended and that safe conditions have returned. Consequently it is not safe yet for locals and volcano tourists to climb the tephra ring and to enter the crater. Volcanologists working on the active volcano, however, have to decide responsibly for themselves.

8. Posteruptive processes at maar–diatreme volcanoes

After the eruptive phreatomagmatic activity has ended groundwater will enter the diatreme and saturate the pore space. Generally, a lake will form on the crater floor, because the crater floor has cut the original groundwater table, thus re-establishing the regional or local groundwater table. After Ukinrek East Maar had erupted from 2–9 April 1977, for the rest of the month of April until the ?middle of May the crater floor was dry, but “by May 20, water had begun to pool in the crater floor…”. Prior to July 1979 the lake level must have reached the local groundwater table at that time (Kienle et al., 1980; Büchel and Lorenz, 1993). Thus it seems to have taken a month for the clastic diatreme fill to be more or less saturated by groundwater.

As long as the steep crater walls are unstable they will continue to collapse and form additional rock falls, slumps, block falls, collapse breccias, and the tephra from the tephra ring will slump and form subaerial grain flows and subaqueous debris flows and turbidites in the crater lake. Later “ordinary” erosion will take over. In April 1977, the crater walls of Ukinrek East Maar in the country rocks were nearly vertical, despite the fact that the exposed country rocks are not hard rocks (Büchel and Lorenz, 1993). In 2004 a large part of the slope of these country rocks in the crater walls was close to the angle of rest. Only in the remaining steep sections do block, lapilli and ash falls still occur regularly (Pirrung et al., in press).

During both biogenic and clastic lacustrine and other types of fluvial, deltaic, alluvial, and eolian sedimentation on the crater floor and crater walls the underlying diatreme fill will compact, dewater and go through extensive diagenetic alteration (Lorenz et al., 2003; Suhr et al., in press). It has been demonstrated for two Oligocene maar–diatremes in eastern Saxony, Germany, that compaction of their diatreme fills has continued through the last 27 million years and that at the larger maar (Kleinsaubernitz) the maar crater and some younger (Miocene) sediments have subsided in excess of 200 m already (Fig. 4) (Lorenz et al., 2003; Suhr et al., in press). In principle, compaction and diagenetic alteration of diatreme fills and overlying maar crater sediments is relatively high initially, then slows down and finally will asymptotically approach zero. Womer et al. (1980) point out that after the phreatomagmatic eruptions of the late Pleistocene to Holocene Split Butte maar, the Snake River Plain, Idaho, a magmatic phase resulted in a lava lake inside the maar crater. After its solidification a pit crater of 420 m in diameter (today) and about 20 m in depth formed. It is suggested here, that this pit crater probably formed because of compaction and subsidence of the tephra fill inside the underlying diatreme. The Holocene Marteles maar on Gran Canaria clearly shows a semicircular active fault

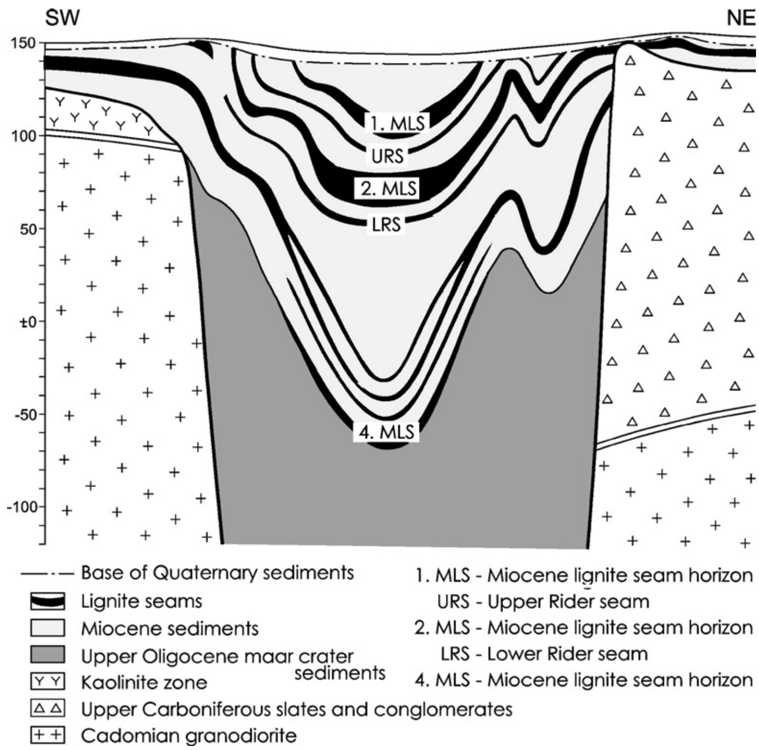

Fig. 4. Posteruptive subsidence and deformation of Miocene lignite bearing sediments above the Oligocene Kleinsaubernitz maar–diatreme volcano in Eastern Saxony as a result of diagenetic compaction and alteration of the underlying diatreme fill (after Lorenz et al., 2003). Vertical scale is ten times the horizontal scale.

on its crater floor and thus provides evidence of ongoing differential subsidence of the underlying diatreme fill (Schmincke, 2000: Fig. 12.13, 2004: Fig. 12.21).

Depending on climate and relief, after the maar eruptions have ended rain-induced aerial, stream, and eolian erosion of tephra will cause fast removal of the distal tephra blanket, which might last a couple of years only. Removal of tephra from the tephra ring by the same erosional processes leads to reworking and redeposition of the tephra. Surface waters will repeatedly be filled more or less with tephra clasts and solvents and their drainage pattern may change. Depending on the relief posteruptive lahars originating in the tephra ring might flow downslope and into neighbouring valleys until the tephra ring is stabilized by a cover of vegetation or becomes indurated diagenetically.

Depending on the climatic conditions and vegetation reclaiming the tephra ring and crater in the years, decades and centuries following the eruptions, erosion by water will lower the tephra ring, widen the crater and deposit eroded material both inside the crater (making the crater floor shallower) and also outside the tephra ring. In addition wind will erode the fines from the surface of the tephra ring, as is still the case at Ukinrek East Maar 27 years after it had erupted.

Depending on the chemistry of the mixture of tephra clasts and of posteruptive gases still released from the feeder dyke (and late intrusive bodies inside the diatreme, see below) there may be intermittent effects on the chemistry of the local groundwater, the lake water and surrounding surface waters. In a number of Eifel maar–diatreme volcanoes the diatremes are used as channelways for rise of CO_2, even several hundred thousand years after their formation and cooling of their feeder dykes and intrusive bodes.

9. Posteruptive hazards of maar–diatreme volcanoes

If it seems obvious that the maar crater will not erupt anymore it might still be very dangerous to enter the maar crater because of unstable crater walls and also because the crater floor may still partially collapse to some extent as the underlying diatreme fill is in an unconsolidated and thus unstable condition, possibly for years to decades. Other hazards which might occur in posteruptive time and the effects of which may, in part, be similar to those of equivalent syneruptive hazards of maar–diatreme volcanoes (see above) and may be largely similar to those of hazards after tephra-eruptions of composite volcanoes are:

1. Outside the maar crater: lahars from tephra deposits flowing onto neighbouring slopes, low areas, and into neighbouring valleys.
2. Erosion by rainwater and streams and deposition of reworked tephra in surrounding low areas. Both 1 and 2 might damage fresh and waste water systems. Eolian erosion (see above) taking out the fines and causing health problems.
3. Rock falls and slumping of country rocks from lower crater wall, formation of unstable scree slopes into lake, respectively onto a dry crater floor (e.g. Moreaux et al., 2004).
4. Slumping of tephra, formation of lahars, and fall of blocks from tephra into crater lake, respectively onto crater walls and floor.
5. Small earthquakes due to sudden subsidence processes within diatreme fill and readjustment of stresses in subvolcanic levels.
6. Release of juvenile gases juvenile gases (CO_2, CO, SO_2, H_2S, HCl, HF, Rn, etc.) from feeder dyke or late intrusive bodies inside the diatreme (Kienle et al., 1980; Varekamp and Rowe, 2000) and gases (CO_2, CH_4, etc.) from lake water). In 1986 the release of CO_2 from the 200 m deep Nyos maar crater lake in Cameroon caused the death of about 1700 people and countless birds and animals (Lockwood et al., 1988; Baxter and Kapila, 1989; Freeth and Kay, 1990; Cotel, 1999; Baxter, 2000; Kusakabe et al., 2003). And previously, in 1984, a similar gas release from Monoun maar crater lake, 100 km south of Lake Nyos, caused the death of 35 people (Baxter and Kapila, 1989, Baxter, 2000; Kusakabe et al., 2003). Such “explosive” release of gases from maar lakes may only be possible where there is no water overturn in wintertime.
7. Because superheated “hot” steam may still leave the crater floor for some time there may be health hazards (thermal burns) for animals and people (Baxter, 1990). 114 d after the eruptions had ended in the Ukinrek West Maar hot spring water on its crater floor had a temperature of 81 °C (Kienle et al., 1980). And at the site of the 1965 phreatomagmatic eruptions of Volcano Island, Taal Volcano, Philippines, hydrothermal discharge at the site of the 1965 eruption on Volcano Island led to a local rise in lake water temperature to a 77 °C (Moxham, 1967).
8. If the crater lake reaches a level above the preeruptive surface, as it had already in Ukinrek West Maar some time prior to July 2004 (Pirrung et al., in press), the tephra ring against which the crater lake is dammed may fail locally and water may suddenly rush down slope or down a valley, as is feared for Lake Nyos (Lockwood et al., 1988; Freeth and Kay, 1990). At Lake Albano, Colli Albani volcano, Italy, such overflows, induced by oscillations in lake level, have repeatedly caused extensive damage by lahars downstreams and may pose, possibly even today, a hazard for Rome (Funiciello et al., 2003).
9. Formation of a lake by damming of a stream by the tephra ring in the valley within which a maar may have formed. If the tephra ring damming such a lake fails as happened at the maar Riñinahue in the Nilahue valley (located downstream from the younger maar Carrán) about two months after its eruptions had ended in 1907, lake water rushed down the valley and devastated part of the valley floor downstream (Illies, 1959).

10. Hazards of maars with intermittent or final magmatic phase

In many maars, worldwide, phreatomagmatic eruptions changed to magmatic eruptions because groundwater was used up, intermittently or for the rest of the volcanic activity. Depending on the amount of magma still rising in the feeder dyke after the end of the phreatomagmatic eruptions, magma intruded the root zone, the diatreme, and finally reached the crater floor. As most maar–diatreme volcanoes are related to basic to ultrabasic magmas most final magmatic phases inside maar craters lead to the formation of scoria cones or even lava lakes in a final magmatic phase, for example scoria cones in the West Eifel and East Eifel volcanic fields, or to lava lakes as in many of the 13 Tertiary volcanic fields in Germany and other Quaternary and Tertiary volcanic fields worldwide (e.g. Camus, 1975; Schmincke, 1977; Emilia et al., 1978; Lorenz and Büchel, 1980; Houghton and Hackett, 1984; Lorenz, 1985, 1986; Houghton and Schmincke, 1986; Houghton and Nairn, 1991; Aranda–Gómez et al., 1992; Konecný et al., 1995; Houghton et al., 1996; Schmincke, 2000; Neuffer and Lutz, 2000; Vespermann and Schmincke, 2000; Lorenz et al., 2003; Konecný et al., 2004; Schmincke, 2004; Martin and Németh, 2004). Such a magmatic phase does not preclude, however, further phreatomagmatic phases (Schmincke, 1977).

In case of intermediate to acidic maar–diatreme volcanoes a final magmatic phase can lead to intrusions in the root zone and diatreme and at the surface these magmas can be emplaced as extrusive domes and coulees (e.g. Camus, 1975; Brooker et al., 1993; Fink and

Andersen, 2000; Nairn et al., 2001; Lorenz and Haneke, 2004).

The hazards associated with an intermittent or a final magmatic phase of emplacement in a maar–diatreme volcano of hot magmatic pyroclastic deposits (scoria), a lava lake, lavas flowing away from the crater, or an extrusive dome with its potential block-and-ash flows will not be discussed here. For these, relevant literature includes: Blong, 1984, 2000; Latter, 1989; Luhr and Simkin, 1993; Sigurdsson et al., 2000; Nairn et al., 2001; and Riedel et al., 2003.

11. Suggestions for hazard maps

For volcanic emergency planning, especially community preparedness and evacuation planning and also medical preparedness, a hazard map (hazard source and hazard targets, Szakács, 2004) should be prepared taking into account the relief, main wind directions, settlements, industries including chemical factories and storage facilities of dangerous or toxic materials, utilities, and transport lines/life lines above and below ground. As a schematic example a hazard map for a maar–diatreme volcano forming in a valley provided with a number of transport lines and life lines and a small village is given in Fig. 5.

11.1. In case only one maar erupts

Hazard zone 1: The area with absolute destruction above and below ground is the area of the actual crater below the level of the preeruptive surface. After other initial volcanic hazards it is ultimately affected by collapse and slumping of all infrastructure (above and below ground) onto the growing crater floor and by subsidence within the diatreme. The longer the activity

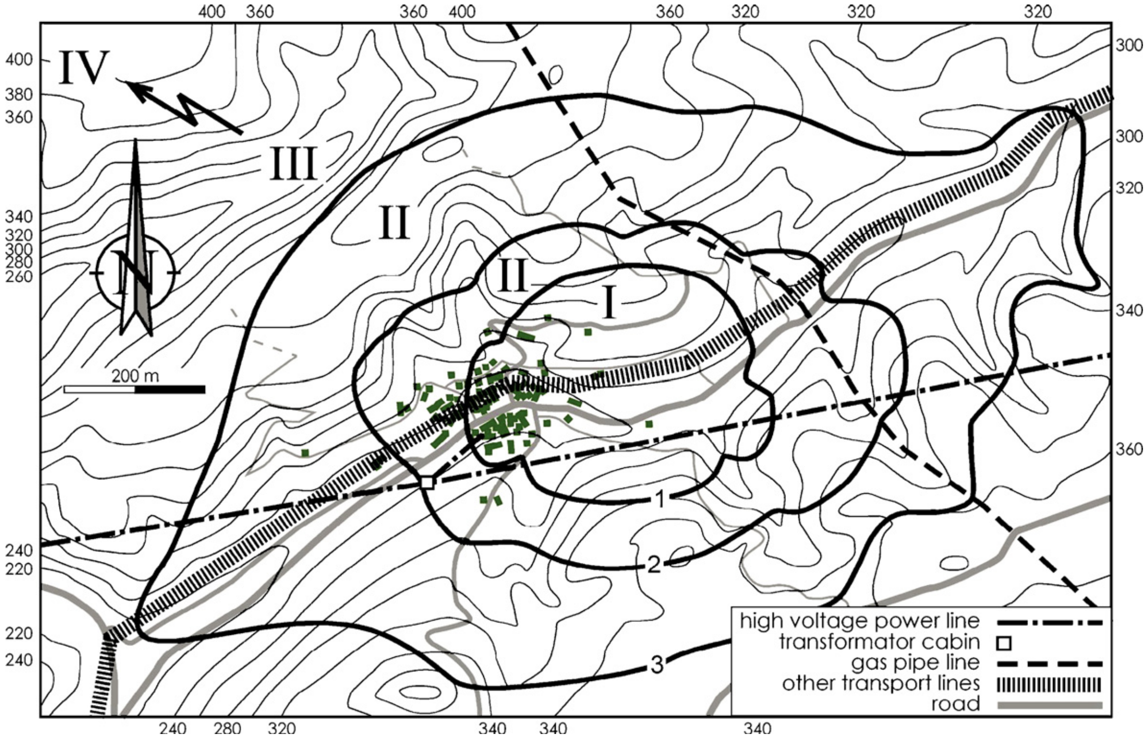

Fig. 5. Hazard map of one schematic maar–diatreme volcano with suggested hazard zones I–IV, assuming a maar–diatreme eruption in a valley incised into hard rocks. The line 1 separates the crater below the preeruptive ground from the tephra ring, the line 2 inside hazard zone II represents the crater rim on the tephra wall, and line 3 represents the outer margin of the tephra wall. In the valley a small village with the name Madivo is assumed to occur. A series of transport lines/life lines are assumed to supply the village or pass through or near the village, the latter in part above and in part below ground. Above ground there could be paved roads and field roads, high and low voltage power lines, telephone lines, a transformer and mobile phone relay stations; below ground there could be high or low voltage power cables, telephone cables, oil, gas, and water pipe lines, and a sewage pipe line system. After the eruptions most of the village Madivo is completely destroyed by the non-circular collapse of the maar crater (hazard zone I), the remaining part will be partially destroyed but covered by the tephra ring (hazard zone II). The high-voltage power line (above ground) will have been destroyed whereas the underground oil- or gas-pipeline east of the crater could still be functioning if not broken by earthquakes. The detailed transport (roads) and life line system inside the village connecting all houses is omitted from this hazard map as are the field roads outside the village. In the hazard zones III and IV there may be diverse but less intensive hazards.

of the maar–diatreme continues the larger hazard zone 1 becomes at the expense of the inner parts of hazard zone 2. This roughly circular to elliptical hazard zone 1 starts with a small diameter (several tens of meters) but can grow up to a diameter of 1000 m or, in case of unconsolidated country "rocks", even more.

Hazard zone 2: The whole area of the tephra ring with large-scale destruction (decreasing in intensity radially outward). This zone is the area of the circular to elliptical tephra ring. Destruction of surface infrastructure by base surges, ballistic blocks and bombs, and by weight of thickening tephra ring. "Survival" of most underground infrastructure as long as they do not cross hazard zone 1. Because of increase in slope of the tephra ring and consequent larger run-out distance of base surges, the longer the phreatomagmatic activity of the maar–diatreme volcano lasts the larger hazard zone 2 gets. The outer margin of the circular to elliptical hazard zone 2 may have a radius of about 1–5 km when measured from the centre of the maar crater. The size of both hazard zones 1 and 2 depend on the length of the volcanic activity and the production rate per unit time as well as on the hydrogeology and thus groundwater availability per unit time.

Hazard zone 3: The medial area with distal effects of some faster flowing or more extensively pulsed base surges and their deposits; deposition by fall of large to small sized lapilli and ash grains. Some destruction of infrastructure possible (e.g. collapse of roofs by wet or dry ash and lapilli fall, injuries to people and animals, some destructive effects on vegetation and crops). The outer margin of this hazard zone 3 is not known yet but may be dependent on the wind direction and wind speed thus it will extend more downwind in comparison to other directions.

Hazard zone 4: The distal area up to distances in excess of 150 km; downwind effects by drifting tephra clouds and ash deposits on air and road traffic, on fresh and waste water systems, vegetation, crops, and health effects on animals as well as on people. The area of hazard zone 4 will extend along the main wind directions and will also depend on the wind speed at various elevations.

It has to be realized that during the eruptions the wind may change and thus the maximum extent and orientation of hazard zones 2–4 will change accordingly.

Emergency management: People and domestic animals should be evacuated from hazard zones 1–3 immediately and industrial processes and the infrastructure above ground should be shut down also in the same hazard zones. Thus, at the beginning of the eruptions a circular area of 5–6 km radius should be evacuated and shut down. The infrastructure below ground (transport lines/life lines) crossing the growing hazard zone 1 should be shut down in the respective corridor through all hazard zones. Bypass transport lines and corridors should be planned and be prescribed. Evacuation of people and domestic animals from parts of hazard zone 4 might be necessary.

11.2. In case two or more maars erupt next to each other

In case two or more maars erupt simultaneously or one after another on the same eruptive fissure or from neighbouring ones as did the Pleistocene Boos maars in the West Eifel (Lorenz, 1973; Lorenz and Zimanowski, 2000) the hazard zones 1–3 (Fig. 5) will become elliptical to 8-shaped. Hazard zone 4 will almost be as if only one maar would have erupted. The emergency management should be handled accordingly.

11.3. In case maars and scoria cones (and associated lava flows) erupt from a volcanic system

In case maars and scoria cones (and associated lava flows) erupt simultaneously or one after the other from the same fissure system, as e.g. happened at the Boos, the Bad Bertrich, the Meerfeld–Mosenberg, or the Pulvermaar volcanic systems in the Westeifel Volcanic Field (Lorenz, 1973; Lorenz and Büchel, 1980; Lorenz, 1985, 1986; Lorenz and Zimanowski, 2000). At the Boos fissure system 12 individual volcanoes (2 maars and 10 small scoria cones) erupted from a fissure system up to 3 km long. In such a case the hazard zones 1–3 will also be elliptically, and the crisis management of the maar and scoria cone eruptions should also be handled accordingly.

12. Areas of potential future phreatomagmatic maar–diatreme eruptions

Areas where future phreatomagmatic eruptions and formation of new maar–diatreme volcanoes might occur exist in all presently active continental volcanic areas or on volcanic islands, especially in those areas which in the past had such phreatomagmatic activities: around the Pacific (e.g. Yamamoto et al., 1991; Aranda–Gómez et al., 1992; Mirabueno, 2004), the volcanic belt extending from China and Indonesia (e.g. on the foot plains of the polygenetic volcano Lamongan (Carn, 2000; Scharf et al., 2000), through Pakistan, Afghanistan, Iran (e.g. Milton, 1978), Turkey (e.g. Keller, 1974; Toprak, 1998), into southern Europe (Greece, Italy, as, e.g. in the Campi Flegrei with its youngest phreatomagmatic eruption (Monte Nuovo) in 1538 (Di Vito et al., 1987;

Mastrolorenzo, 1994; Dellino et al., 2001) and in the Alban Hills where the most recent eruptions occurred about 5000 a B.P. (Chiarabba et al., 1997; Funiciello et al., 2003); East Africa and along the Red Sea and Dead Sea Rift; in young monogenetic volcanic fields such as, e.g. in the Chaîne des Puys, France, with its youngest maar, the trachytic Lac Pavin maar (6700 a B.P.) (Aeschbach-Hertig et al., 2002; Moreaux et al., 2004), and in Germany (West and East Eifel), with its youngest maar (10,000 a B.P.), the hauyne melilite nephelinite Ulmen Maar (Mertes, 1983; Lorenz and Zimanowski, 2000). For Quaternary monogenetic fields recurrence rates should be established in order to learn about future eruptions and associated hazard potentials, be it maar or scoria cone eruptions (Condit and Connor, 1996; Conway et al., 1998; McBirney, 2004). All active volcanic islands, such as Oahu with its Honolulu Series and the youngest eruptions perhaps 35,000 a B.P. (Garcia, 2001), North Island, New Zealand with its Auckland Volcanic Field and its many Holocene maars and the youngest eruptions less than 1000 years ago (Smith et al., 1998), and in southern Australia with its youngest eruptions 4500 a B.P. (Cas et al., 1993; Cas, 2001) are also areas of potentially new phreatomagmatic activity. Wherever magma rises in relatively small volumes to the surface and interacts at shallow depth with groundwater or surface water the consequent phreatomagmatic explosions result in phreatomagmatic eruptions, the formation of maar–diatreme volcanoes, (or tuff-ring-diatreme, tuff-cone-diatreme, or tuff-cone volcanoes), in monogenetic fields, but also on polygenetic volcanoes. High magma production rates and simultaneous respective large quantities of external water, as is typical for the environment of many composite volcanoes and caldera volcanoes (as, e.g. at Campi Flegrei, Italy, Santorini, Greece, Krakatau 1883, Indonesia, Taupo, New Zealand) may result in phreatoplinian eruptions and water-cooled ignimbrites (e.g. Self and Sparks, 1978; Camus and Vincent, 1983; Self, 1983; Walker, 1983; Orsi et al., 1992; Houghton et al., 2000; De Rita et al., 2002).

The volcanological and associated hazard studies on the relatively small maar–diatreme, tuff-ring, and tuff-cone volcanoes will help improve understanding of many subsurface volcanic processes associated with small or large phreatomagmatic basic, intermediate, and acidic eruptions of the subaerial polygenetic volcanoes of the world, many of which are located in densely populated areas (Walker, 1983).

13. Immediate response to maar–diatreme eruptions

Based on the experience in the last century that maars erupted for only days to weeks, a very rapid response to initial maar eruptions by installation of a team of volcanologists and geophysicists on site (provided with a helicopter and a 4×4 vehicle) should be aimed for — even if the eruptions occur in isolated, i.e. non-populated areas. In case maars, tuff-rings or tuff-cones erupt in populated areas, an operational model for the emergency stage should be implemented (D'Ascia, 1998) at the very beginning — or in case of identifiable precursory activity, even prior to the eruptions. Judging from the tephra ring deposits of maar–diatreme volcanoes the volcanic activity may reach full intensity from almost the very beginning. Some important aspects of such an operational model imply that from the very beginning of the eruptions, medical doctors specialised in the various (eruption-induced) physical injuries and in emotional trauma should form a fast response team and be within easy reach. Organisations specialized in evacuation campaigns and special industrial and other utility safety aspects should also form a fast response team and be within easy reach. Public officials (leaders, planners, and emergency managers) should form a team with the other three groups for making informed sensible decisions in order to form a disaster relief unit responding to the volcanic and other hazards and handling the various emergencies accordingly. Representatives of all four groups should get together as soon as such an eruption has started, or in case of precursory activity, prior to the eruptions, and cooperate responsibly from the initial signs of the expected eruptions onwards (Daly and Wood, 1998; Daly et al., 1998; Houghton, 2003). In addition to several modern textbooks dealing with volcanic disasters and society and cited in the references, the abstract volumes of the 4 meetings "Cities on Volcanoes" held in the past (see Cities on Volcanoes (I): 1998, II: 2001, III: 2003, IV: 2006, Stewart, 2001), the abstract volume of the IAVCEI General Assembly held in 2004 in Pucón, Chile are very valuable in acquiring basic knowledge on volcanic hazards, eruption effects on society, emergency planning, and crisis management.

14. Suggestions for hazard studies and monitoring

The Ukinrek Maars which erupted in 1977 in Alaska, are the maars studied best during their eruptions and in early posteruptive time (Kienle et al., 1978; Self et al., 1980; Kienle et al., 1980; Büchel and Lorenz, 1993; Ort et al., 1993, 2000). However, there were no observations from close distances and no real monitoring during the eruptions. Since maar–diatreme volcanoes represent the second most common volcano type in subaerial environments and many volcanic areas are areas of high population density and increasingly sophisticated infrastructure (Andreastuti and Voight, 2003; Houghton, 2003), there is an urgent need for more detailed hazard related studies of the most recent maar, tuff-ring, and tuff-cone eruptions and of older well preserved maars, tuff-rings, and tuff-cones. In addition there is a definite need for such detailed hazard studies and monitoring of future phreatomagmatic eruptions leading to the above volcano types.

The following volcanological and non-volcanological hazard-related studies should be performed during the eruptions and after the eruptions have ended:

14.1. Syneruptive studies and monitoring

1. Geophysical studies, especially of the seismic activity, acoustic activity, and generation of short-term electrostatic field variations (Büttner et al., 1997, 1999; Röder et al., 1999; Büttner et al., 2000; Röder et al., 2002; Zimanowski et al., 2003), etc.
2. Intensive video-supported studies of the phreatomagmatic eruptions including eruption clouds, formation of base surges, their velocity and run-out distance, tephra materials, ejection of ballistic bombs and blocks, and timing of individual events.
3. Detailed study of the growth of the maar crater
4. Measurement of the relevant low- and high-level meteorological parameters.
5. If possible study of the evolution of near-surface aquifers in the vicinity of the maar–diatreme volcano.
6. Effects of eruptions on people, animals, settlements, industry, utilities, transport lines/life lines, and environment.

14.2. Short- and long-term posteruptive studies and monitoring

As there are short-term and long-term posteruptive processes at maar–diatreme volcanoes, which have not been quantified yet, respective studies and monitoring should be performed.

1. Quantification of the posteruptive changes in shape, diameter and depth of crater, in shape of tephra ring (erosion and sedimentation processes). Subsidence of crater floor by compaction of diatreme fill.
2. Studies of the reestablishment of the aquifers and the formation of crater lake, including study of the evolution of hydrophysics, hydrochemistry, hydrobiology of the maar lake, as well as study of gases released at depth or dissolved at depth in the lake body and lake sediments.
3. All the maars which erupted in historic time, such as the Ukinrek Maars and the Nilahue/Carrán maar, and a number of well exposed Holocene maars should be reinvestigated in detail to establish representative case histories as a guide to future maar–diatreme eruptions and the volcanological hazards this second most common subaerial volcano type poses for people, settlements, industry, utilities, infrastructure, animals, and environment.

Acknowledgements

At the IAVCEI congress held in 1993 in Canberra, Tom Casadevall asked me what kind of decisions public officials and volcanologists have to make if a maar erupted in the maar-rich densely populated foot plain of a composite volcano in Indonesia. The foot plain was struck by earthquakes and possibly magma rising from beneath the composite volcano could erupt in the foot plain and a new maar could form in this particular maar-prone environment. This question and the international interdisciplinary meetings Cities on Volcanoes I, held 1998 in Rome and Naples, Italy, Cities on Volcanoes II, held 2001 in Auckland, New Zealand, and the 2nd International Maar Conference held 2004 in Hungary, Slovakia and Germany provided the motivation for this study. I gratefully acknowledge Tom Casadevall and the organisers and participants of the above meetings for their stimulating questions and contributions. The intensive cooperation with Ralf, Büttner, Georg Büchel, Kurt Goth, Stephan Kurszlaukis, Michael Pirrung, Peter Suhr, and Bernd Zimanowski has been very productive in understanding the complex volcanic processes at and beneath maar craters as well as posteruptive processes at this unusual volcano type. Wolfram Schumann and Luca Nano produced the computer graphics. Larry Mastin, Shane Cronin and James White are gratefully acknowledged for their highly constructive reviews. The provision of funds by DFG, Bonn, Germany, to participate in international volcanological meetings and the provision of funds for my research on maars and diatremes over several decades by DFG, NASA, and the institutes, respectively departments of geology or geosciences at the Universities at Mainz, Eugene/Oregon and Würzburg is also gratefully acknowledged.

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