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MORPHOMETRY, LIMNOLOGY, HYDROLOGY AND SEDIMENTOLOGY OF MAAR LAKES IN EAST JAVA, INDONESIA

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Abstract

In the volcanic arc of Java, Indonesia, maar lakes exist around the Lamongan-Tarub stratovolcano and north of Tengger Caldera in East Java. Geological, morphometrical, hydrological, limnological, sedimentological and geochemical data are presented from the maar lakes Ranu Agung, Ranu Lading, Ranu Segaran and Ranu Klindungan. Lake sediments are discussed with respect to their potential as climate archives. Severe problems for the maar lakes resulting from high population pressure and intense agriculture are highlighted.

Key words: East Java, Lamongan, Tengger Massif, limnology, maar lake sediments

INTRODUCTION

On a global scale maars range second after scoria cones as most frequent volcanoes (Lorenz 1987). Maars consist of a tuff wall with pyroclastics (tephra) rich in xenolithic rock fragments. They surround a crater at least initially filled with water as the local ground water table is usually deeper than the rim of the crater. The crater itself is above a diatreme (or tuff pipe) filled with lapilli and ash tephra, breccia and feeder dykes. Maar craters are ideal sediment traps and potential climate archives (Brauer *et al.* 2000). Some fossil rich Tertiary maar lakes in Germany, like Eckfeld Maar in the Eifel, Grube Messel on Sprendlinger Horst and Enspel in the Westerwald (Pirrung *et al.* 2001), were formed under subtropical climate. Already Hummel (1925) compared modern maar lakes in East Java with the Middle Eocene maar lake Messel. In East Java, maars are clustered around the Lamongan-Tarub stratovolcano and a single maar, Ranu Klindungan, is located at the northern slope of the Tengger Caldera, a collapsed stratovolcano (Fig. 1). Geochemistry, petrology and morphometry of the Tengger Caldera and the Lamongan Volcanic Field was investigated by van Bemmelen (1970), van Gerven & Pichler (1995), Carn (2000) and Carn & Pyle (2001). The volcanic rocks are basalts and basaltic andesits or transitional basalts and their chemical characteristics are typical for subduction-related volcanics (Heublein 2002). Lava flows from the Lamongan and Tarub volcanoes consist of fine grained basalts or basalts rich in plagioclase phenocrysts. The thickness of these lava flows exceeds 5 m at Ranu Lading and 20 m at Ranu Agung (Heublein 2002, Theune-Hobbs 1999). Maar tephra frequently consist of brown bloc- and lapilli-bearing ash tuffs and lapilli tuffs with ejected blocs of older basaltic lava flows.

Due to intensive laterite formation geological mapping is difficult in the Lamongan Volcanic Field, and outcrops on the lower slopes of the Lamongan-Tarub volcanoes are rare. However, in aerial photos (Fig. 2) the extent of lava flows erupted in the 19th century from fissures on the southwestern flanks of Lamongan volcano could be mapped excellently, as these aa-lavas are only sparsely covered by vegetation and at their lower end a 2–5 m high front is developed. They are fresh or only weakly weathered. Older lava flows are covered by soils and often used for plantations.

Climate in East Java is dominated by the dry southeasterly monsoon from June to October and by the moist northeasterly monsoon from November to May, resulting in a dry and wet period, respectively (Trihadiningrum *et al.* 1996). In East Java, annual precipitation is 1300 mm/yr at Pasuruan (Fig. 1), at about 15 m a.s.l. (Scharf *et al.* 2001), whereas at Klakah, located at 250 m a.s.l. on the western slope of the Lamongan volcano (Fig. 2), precipitation is 2400 mm/yr (Sporrer 1995). Mean annual temperature is 26.2°C at Pasuruan. During El Nińo Java suffers from severe droughts, while precipitation is enhanced during La Nińa (Harger 1995).

The maar lakes in East Java were studied in detail, for example, by Ruttner (1931), Sporrer (1995), Green *et al.* (1996), Scharf *et al.* (2001). We give an overview about the morphology of 10 maar craters and discuss the age of the maars. For an illustration of the morphology, limnology and sedimentology we chose those lakes as an example, where the most detailed observations are available: for the morphology, limnology and hydrology we present Ranu Agung, sedi-

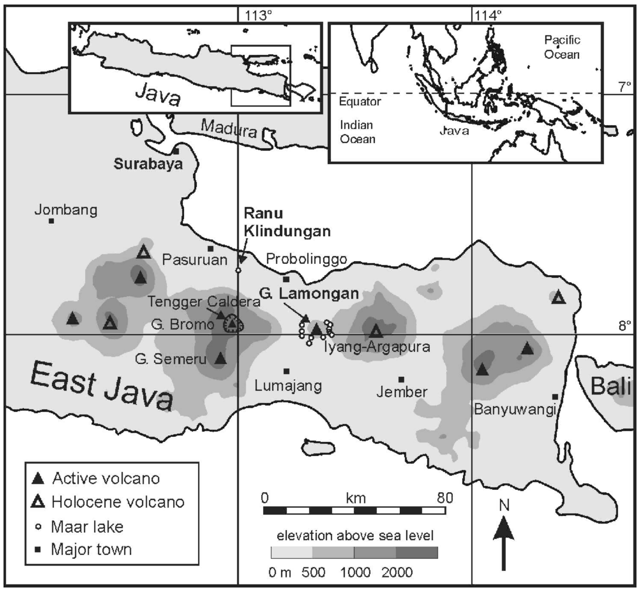

Fig. 1. Location of maar lakes in East Java. Modified after Scharf *et al.* (2001).

mentological processes are discussed for Ranu Segaran and geochemical variations are reported from Ranu Klindungan.

METHODS AND MATERIAL

For a comparison between sediments of the above mentioned Tertiary maar lakes and recent sediments of tropical maar lakes, we performed several expeditions to Java between 1996 and 2003.

Topographical surveys were performed using a TOPCON ET-2 Totalstation or a GARMIN GPS12. The transparency of the lake water was determined using a Secchi disk. Physicochemical parameters (pH, electrical conductivity calculated for a temperature of 25°C, temperature, oxygen content) were measured on water samples collected with a HYDROBIOS 5 l water sampler using the WTW tools Oxi 320, LF 320 and pH 320, or with a multiparameter-probe IDRONAUT Ocean Seven 316, calibrated to lake water (Scharf *et al.* 2001). Sediment cores were retrieved using a NIEDERREITER Mondsee corer. The numerous nets fixed to the ground in one of the lakes, Ranu Klindungan, limited the area for core locations. Thin-section analysis was performed using a LEITZ DMRDP light microscope with 50 to 500 x magnification using parallel or crossed nicols. Alternating biogenous layers (with sublayers rich in diatom frustules and calcite crystals) and terrigenous layers (with minerogenic silt, fine sand grains and frequent intraclasts) were marked on the scanned thin sections to establish a varve chronology. Magnetic susceptibility was measured on the sediment surface covered by a thin plastic film with a BARTINGTON E-sensor connected to a MS2 susceptibility meter at 1 mm vertical resolution and corrected for the drift of the sensor (for details see Scharf *et al.* 2001). On slabs of sediments impregnated with BASF Palatal P-80-02 resin, produced for thin section preparation, elemental analysis was performed on a VG ELEMENTAL PlasmaQuad PQ3-S Inductively Coupled Mass spetrometer with MERCHANTEK Microprobe II Laser Ablation (ICP-MS-LA) at the Institute of Geosciences in Jena. Profiles were shot at a spatial resolution of 100 µm. For correction of varying ablation rates, elemental counts were divided by isotope abundance and normalised to background-corrected C-values. C is a main component of the resin and present in the pores of the sediment slabs. The background of the C-values results from a minute CO_2 content of the Argon carrier gas.

Details on the core locations, magnetic susceptibility and geochemical data can be retrieved in the PANGAEA information system (http://www.pangaea.de).

MORPHOMETRY OF MAARS IN EAST JAVA

The Gunung Lamongan (1651 m a.s.l.; the Indonesian word ´Gunung´ means mountain; hereafter G.), situated southeast of Probolinggo in East Java, was one of the most active volcanoes in Java in the 19th century (van Bemmelen 1970). Together with G. Tarub (1671 m a.s.l.; 1 km northeast of G. Lamongan), which is an older stratovolcano, G. Lamongan forms the center of the Lamongan Volcanic Field which consists of >60 scoria cones, at least one lava dome, and >32 maars. Towards the west there is no distinct limit of the volcanic field and the larger scoria cones in the western part (Fig. 2) may already be attributed to the Tengger Massif. 13 maar lakes and >18 dry maars surround G. Lamongan at a distance of 3 to 9 km (Fig. 2) in elevations between 175 and 600 m a.s.l. (Büchel, Müller 1998, Carn 2000, Theune-Hobbs 1999, Assing 2001, Heublein 2002).

Ranu Klindungan is an isolated maar crater located at 16 m a.s.l. southeast of Pasuruan at the lowermost part of the northern slope of the 2613 m high Tengger Massif with the Tengger Caldera and the Bromo volcano. With a diameter of 1550 m and a maximum depth of 126 m it is the largest maar lake in Java.

To our knowledge, the only comparative morphometric study of tropical maar craters exists from the Lamongan area in East Java. Carn (2000) analysed satellite images and topographic maps and verified these data by field observations. However, in that study the lake depths were only partly considered. Diameters of the maar lakes around G. Lamongan range between 200 and 800 m and water depths are between 5 and 155 m (Tab. 1). The lakes are named ´Ranu´ (*e.g.* Ranu Agung; the Indonesian word is used for volcanic crater lakes; herafter R.) and the name ´Ranu ...´ of several dry maars around G. Lamongan indicates that the silting up of these lakes has occured during the last decades or centuries.

From the available topographic maps (East Java 1:50000 sheet 128C/129A, Volcanological Department), elevations of the maar craters could not be estimated precisely. The data from Carn (2000) partly differed from our topographic surveys. For example for R. Agung, where the average crater diameter to depth ratio (D/d_{crater}) of Carn (2000) is 7.6, we determined 6.2 (Theune-Hobbs 1999). From published lake analyses (Ruttner 1931, Sporrer 1995) and from depth soundings, echograms (Theune-Hobbs 1999, Scharf unpubl.) and topographic surveys we present new data for the morphometry of craters and lakes (Tab. 1, Fig. 3). In analogy to observations at Quaternary maars in the Eifel (Büchel 1993) and in Alaska (Büchel, Lorenz 1993) the craters have a

Table 1

Morphometry of maar lakes in the Lamongan Volcanic Field compared to dated maar craters in Alaska, the Eifel and Cameroon

Lake	Category	$D_{crater, mean}$ [m]	$d_{crater, subaer.}$ [m]	$D_{lake, mean}$ [m]	$d_{lake, max.}$ [m]	$d_{crater, total}$ [m]	D/d_{crater}	D/d_{lake}	R [km]
R. Pakis	o	910	49	7602	155	204	4.5	4.9	8.21
Ukinrek	*	3073	353	2373	323	673	4.6	7.4	
R. Agung-A	w	540	87	310	25	112	4.8	12.4	5.7
R. Agung-B	w	630	100	350	27	127	5.0	13.0	5.3
R. Lading	w	410	75	210	7	82	5.0	30.0	4.51
Ulmen	*	3704	37	269	36	734	5.1	7.5	
R. Agung-C	w	708	87	440	27	114	6.2	16.3	5.51
R. Gedang		420	62	200	6	68	6.2	33.3	5.51
R. Bedali	w	1060	151	3992	112	162	6.5	36.3	8.41
Pulvermaar	*	9404	50	625	70	1214	7.8	8.9	
R. Betok	w	5931	631	200	5	68	8.7	40.0	4.51
R. Klindungan	d	1750^2	30	1550^2	126	156	11.2	12.3	13.0
R. Segaran	o	730	24	615	40	64	11.4	15.4	7.01
R. Lamongan	o	8302	302	7262	29	59	14.1	25.0	7.71
Mbarombi Mbo	*	3050	81	2300	110	191	16.0	21.0	
R. Logung		490	19	295	6	25	19.6	49.2	7.91

D = mean diameter, d = mean depth of crater, resp. maximum depth of the lake during the dry season; lakes are sorted for increasing D / d_{crater}. The distance R is the horizontal distance from the lake center to the center of the G. Lamongan crater or of the Tengger Caldera. R. Betok is also referred to as R. Tangke, R. Lamongan also as R. Klakah. For the double crater of R. Agung the diameter of the eastern (A) and western half of the crater (B) and a mean diameter of the entire crater (C) is given. In the colum 'category', lakes that have an outlet with regulation of the water table are marked with 'o', a dam is indicated with 'd' and observation of water table fluctuations > 2 m in lakes without dam with 'w'. Marked with *: Ukinrek East maar in Alaska, erupted in 1977 and visited in 1981; Ulmen Maar in the Westeifel, erupted 10000 years BP; Pulvermaar in the Westeifel, erupted 20000 years BP; Barombi Mbo, Cameroon, erupted = 25000 years BP. Data after own measurements, partly after maps, and after [1]Carn (2000), [2]Ruttner (1931), [3]Büchel & Lorenz (1993), [4]Büchel (1993) and [5]Giresse *et al.* (1991).

D/d_{crater} of about 5 immediately after their eruptive activity, whereas this ratio increases to about 10 for increasing ages of the craters due to sediment infill and erosion of the tuff wall. In Tab. 1, some data from dated maars in Alaska, the Eifel and Cameroon are reported for comparison. The maars with D/d_{crater} of 4–5, like R. Pakis, R. Agung and R. Lading, may be only some hundred to some thousand years old, whereas R. Klindungan, R. Segaran, R. Lamongan and R. Logung with a D/d_{crater} of 11–14 may be some ten thousand years old. The question of the age of the craters should however be investigated more in detail, as the tropical weathering in Java may cause different erosion rates within the maars compared to Alaska and the Eifel area.

From the diameter to depth ratio of the lakes, D/d_{lake} (Tab. 1), the age of the lakes cannot be estimated, as other factors influence this ratio as well: the depth of the local groundwater table (which roughly corresponds to the subaerial depth of the crater), the diameter of the maar crater, the depth of the initial crater and the degree of filling of the crater by sediments and/or tephra of a nearby eruption center. As the profundal part of the lake basin is nearly horizontal in all investigated maars, D/d_{lake} must be much higher for a lake connected to a groundwater table in greater depth below the topographic surface, like R. Bedali, compared to a lake with a ground water table close to the topographic surface, like R. Pakis. Both lakes have a similar distance to the G. Lamongan, nearly the same elevation of the water table, a similar crater diameter, but the D/d_{lake} of R. Pakis is 4.9, whereas that of R. Bedali is 36.3.

Some field impressions of the maar lakes in East Java are shown in Fig. 4. For the description of the morphometry of the maar craters we selected R. Agung in the Lamongan Volcanic Field. The meaning of the Indonesian word ´Agung´ means ´great´ and indeed this lake is very impressive because of the steep inner crater slopes, that reach up to 115 m above the normally deep blue lake (Fig. 4A). The lower part of the crater is nearly vertical above the western shore line with >20 m high columns of a basaltic lava. This pyroxen-megacryst-rich basalt is limited to the east by a NNE-trending normal fault with at least 25 m displacement and the basalt is not visibile on the subaerial slopes in the central and eastern part of the crater. However, in echogram profiles (Theune-Hobbs 1999, Scharf unpubl.) the steep western, northern and southwestern slopes are a good argument that the lava continues down to a water depth of >20 m. The shape of the lake is elongated in E–W direction (radial to G. Tarub) with a maximum diameter of 720 m and a minimum diameter of 300 m in NNE–SSW direction between two promontories that indicate the former existence of two separate craters (Fig. 5).

The D/d_{crater} of 4.8–5.0 for the eastern and western basin of the crater points to an age of the crater of less than a few thousand years. The lake has no outlet, but a seasonal inflow from a small, steep valley with an alluvial fan in the south. The groove at the valley floor contains bolders up to 50 cm in

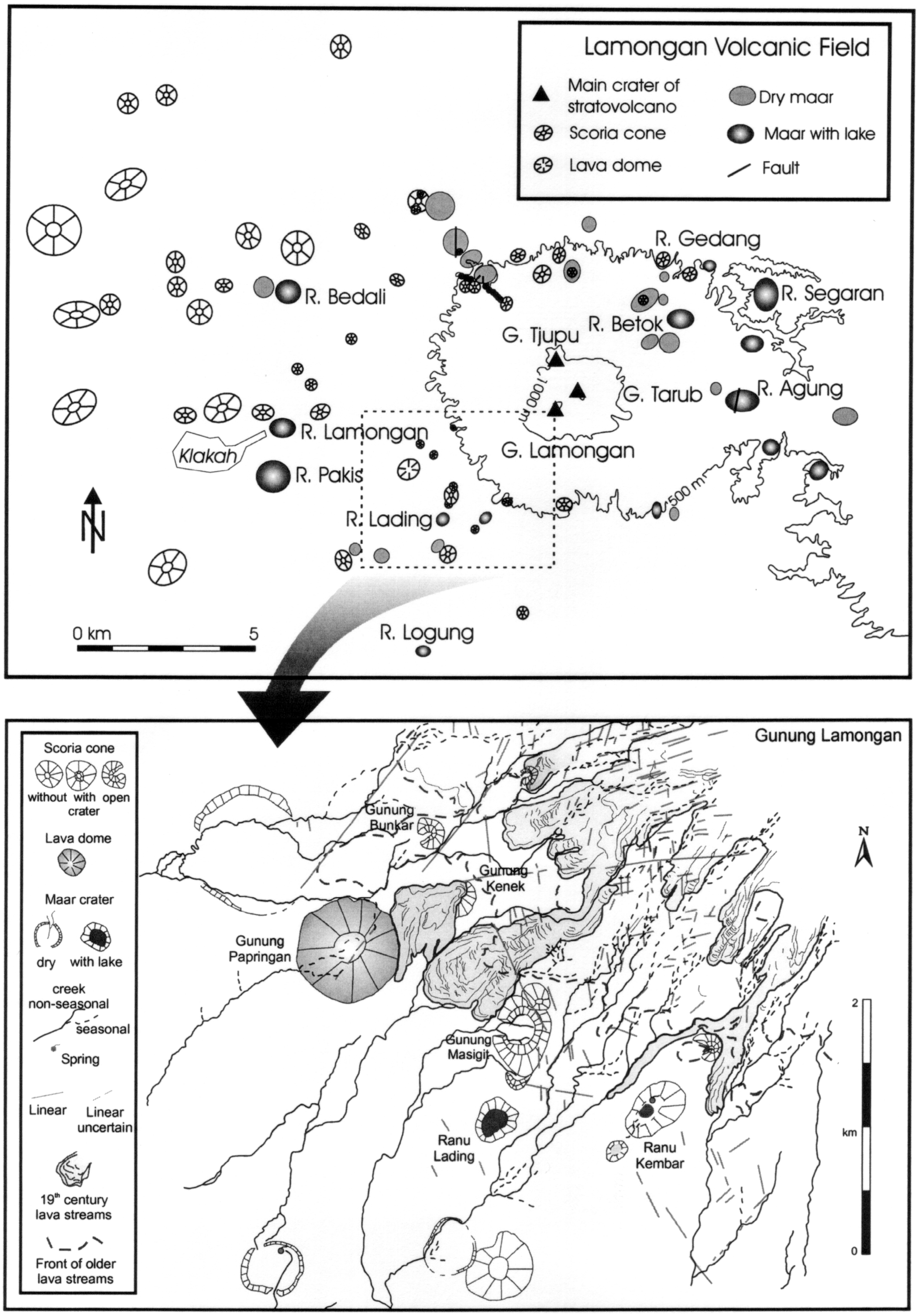

Fig. 2. Scoria cones and maars in the Lamongan Volcanic Field. Modified after Carn (2000). Two dry maars and 19 scoria cones were added to the original map and one scoria cone is now interpreted as a lava dome. The inset shows a photogeological map from the southwestern flank of the G. Lamongan (after Heublein 2002). Apart from flow structures, linears on lava flows erupted in the 19th century are interpreted as active faults.

diameter, which documented significant erosion during the rain season. In September 1997, the front of the fan was formed by a step of 1 m elevation, probably it had been undercut by wave action on stormy days. Another smaller and steeper alluvial fan exists on the northwestern shore. At a thunderstorm on March 20th in 2001, a temporary creek produced fresh grooves on this fan. The subaqueous part of both fans reaches more than 100 m towards the center of the lake.

Preeruptive rocks consist of older pyroclastics and bituminous lake sediments. The 17–28 m thick tephra of the tuff wall are bloc- and bomb-bearing ash and lapilli tephra of maar and tuff ring eruptions. The lowest level of maar tephra

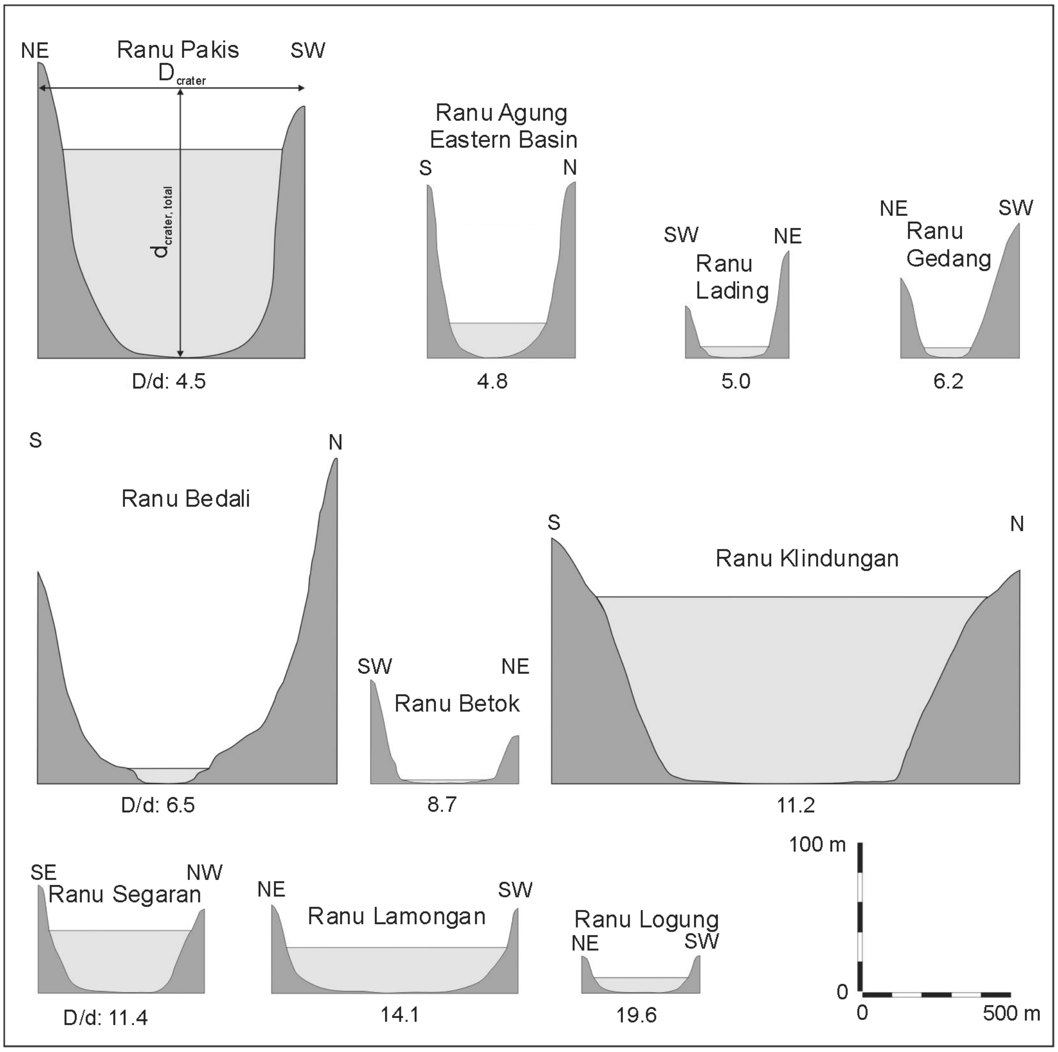

Fig. 3. Morphometry of selected maars in the Lamongan Volcanic Field and of R. Klindungan. The diameter to depth ratio $D_{crater}/d_{crater,\ total}$ increases with the age of the crater. After Ruttner (1931), Sporrer (1995), Scharf *et al.* (2001) and new depth soundings (R. Agung, R. Betok, R. Lading, R. Logung, R. Segaran) and echogram profiles (Ranu Agung, R. Lading, R. Gedang).

is located at the southeastern tuff wall, where a preeruptive valley was dammed by the tephra.

LIMNOLOGY

During the German Sunda expedition in 1928/1929 the limnology of several maar lakes in Java was investigated, but as repeated measurements could not be performed, the mixing characteristics remained uncertain (Ruttner 1931). An overview of the limnology of natural lakes in Indonesia was presented by Lehmusluoto *et al.* (1995). Most tropical lakes showed a distinct stratification, that was permanent or occasionally interrupted by mixing events. From eleven investigated crater lakes in Indonesia, most of them located in Calderas, five were assumed to be monomictic with one complete annual mixis, four to be meromictic without complete mixis, from two crater lakes no data were available, but none was oligomictic with irregular mixis. From Green *et al.* (1996), Ruttner (1931), Sporrer (1995) and Scharf *et al.* (2000, 2001) physicochemical data from the maar lakes R. Klindungan and several lakes in the Lamongan Volcanic Field were presented. In the following, we will report new observations from several field trips to the maar craters in East Java.

The strong seasonality of precipitation is the reason for lake level fluctuations illustrated by observations from R. Agung, R. Lading and R. Segaran. At R. Agung, the lake water table at 485 m a.s.l. decreased by about 20 cm within 4 weeks in September 1997, at the end of the dry season without any precipitation. We could roughly estimate the inflow towards the lake and the evaporation for a hydrological balance. Eight springs surrounded R. Agung at levels of 25–65 m above the lake water table. Only on the southeastern tuff wall there exist no springs. The discharge of the springs was measured on 19th September 1997. Maximum individual discharge was 2.0 l/s and total discharge was 5.7 l/s (or 20.52 m^3/h). About the same amount can be assumed for observed diffuse discharges, so total discharge may be in the order of 10 l/s (36 m^3/h). The discharge of the springs decreased and some even dried up, but as an approximation we could take this value as an average for September 1997. The total discharge during four weeks in September was 24200 m^3, which

A: Ranu Agung

B: Ranu Lading

C: Ranu Lading

D: Ranu Lading

E: Ranu Segaran

F: Ranu Klindungan

Fig. 4. A: Inner crater wall with sparse shrub-vegetation of R. Agung, view towards the east, in the background scoria cones on the western slope of the Argapura stratovolcano, September 1999. B: Dense vegetation on the inner crater slope of R. Lading, May 1999. On the left side, along the southeastern shore line, a small area of submerse vegetation is visible. Areas with smaller trees represent regions of former land slides that occur during the rain season on the steep slopes and are rapidly covered by vegetation. C: R. Lading, view towards the southwestern tuff wall, September 1996. D: Deforested slopes of R. Lading, September 2003 (same view as in C). No submerse vegetation is present. In the background a small land slide is free from vegetation (arrow). The shrub-free lower part of the crater slopes results from the 6 m higher water table during the rain season. E: R. Segaran, September 1996. No submerse vegetation exists. The inner crater slopes are used for plantations of bananas and coconuts. The shrub-free lower part of the crater slope indicates a higher water level during the rain season. F: R. Klindungan, September 2003. In the background the northern slope of the Tengger Massif is visible. The height of the crater wall in the background is about 50 m, the rim of the Tengger Caldera is at about 2600 m a.s.l. The submerse vegetation in the foreground consists of *Elodea* and is developed all along the shoreline. One of the numerous aquacultures is visible.

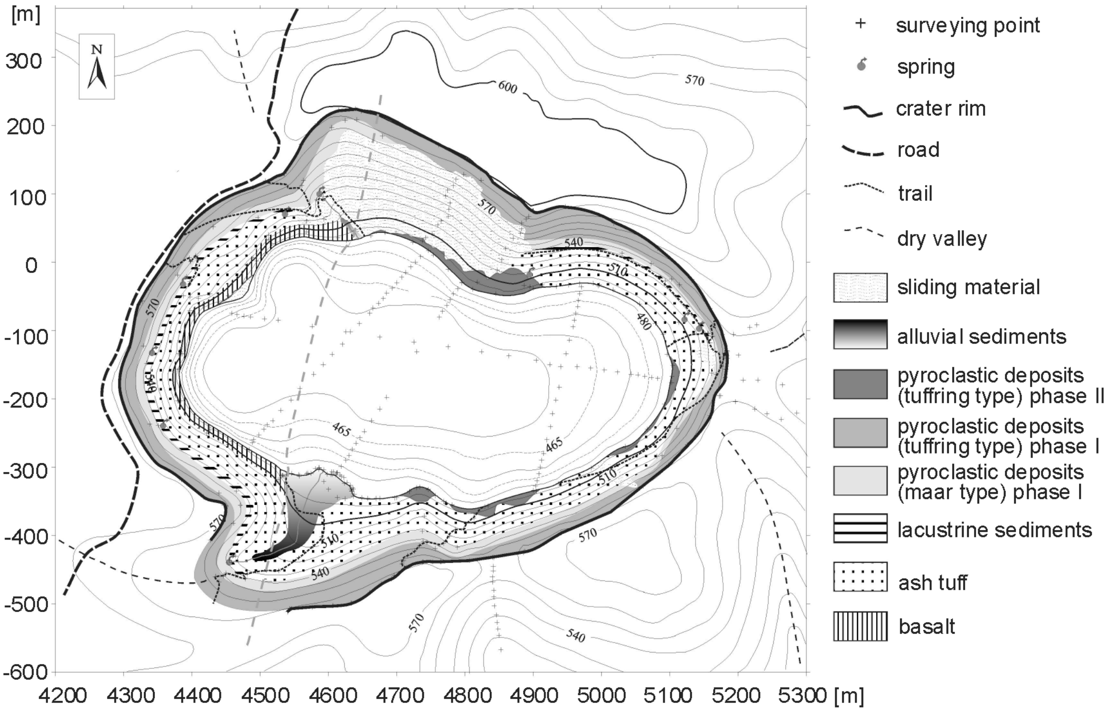

Fig. 5. Geological map of R. Agung (mod. after Theune-Hobbs 1999).

equals 120 mm when it is spread over the area of the lake of 0.202 km^2 (topografic survey in September 1997, the maximum lake depth was 27.1 m). At Ngadisari, located at 1758 m a.s.l. on the eastern slope of the Tengger Caldera, mean humidity was 70% between 13th September and 8th October 2003, measured about 10–20 times a day. At R. Klindungan, at 16 m. a.s.l., we measured an average humidity of 58% during the same time interval. Under the assumption of an average temperature of 25°C and a humidity of 65% at R. Agung for September 1997, we could estimate potential evaporation using the formula by Schendel (1968) as: (mean monthly temperature in °C / mean monthly humidity in %) * 480 = 185 mm/month. This was less than the observed decrease of the water table plus the discharge during September 1997 (320 mm). Groundwater inflows, which may be assumed in the western part of the lake (possibly within the lava flow from G. Tarub), were lower than groundwater outflows, that probably occured in the eastern part of the lake. In March 2001, the lake level was 2.1 m higher than in September 1997. Water marks on the basalt columns documented that the water level must have been at least 2.8 m higher during the rain seasons compared to the lake level in September 1997. The average precipitation at R. Agung at an elevation of 600 m a.s.l. is about 3800 mm per year, interpolated from a map of mean annual rainfall in East Java (Hydrogeological map of East Java, Volcanological Survey of Indonesia). If the value for evaporation in September is extrapolated for the months June to October, and if evaporation during the rain season is about half that of the dry period, mean annual evaporation at the lake surface is in the order of 1560 mm. For the subaerial catchment outside the lake area, which is 0.446 km^2, the effective evaporation may be about 2/3 of the potential evaporation, or 1040 mm. The hydrological balance would be: (lake area / catchment area) * (precipitation – evaporation) + (catchment area outside lake / catchment area) * (precipitation – evaporation) = (0.202 km^2/0.648 km^2) * (3800 mm – 1560 mm) + (0.446 km^2/0.648 km^2) * (3800 mm – 1040 mm) = 2600 mm, if we neglect groundwater inflows and outflows. This value is in the order of the observed lake level variations at R. Agung.

At R. Lading (Fig. 4B) the water depth determined by echograms and depth soundings on 15th August 1997 and 11th May 1999 was 6 and 12 m, respectively. From field observations, maximum lake level fluctuations of 7 m could be assumed for R. Segaran (Fig. 4E). Lake level fluctuations at the maars in the Lamongan Volcanic Field seem to be predominantly caused by seasonal variations in precipitation and evaporation and not by groundwater inflows. However, detailed time series of meteorological and hydrological data from the Lamongan area are necessary for a better understanding of the water budget of the lakes.

HYDROLOGY

New data of R. Agung are presented as example for the hydrology and hydrochemistry of a maar lake in the Lamongan Volcanic Field, to complete the observations of Ruttner (1931), Green *et al.* (1996) and Sporrer (1995). In depth profiles of the lake water, a more or less distinct thermocline resp. chemocline was visible (Fig. 6), separating a well oxygenated epilimnion from a H_2S-bearing hypolimnion. The highest difference in temperature measured (14:00 to 16:00 local time) between surface and bottom water of the lake was on 6th April 1998 (29.2 versus 24.8°C), when the thermocline was at a depth of 10–13 m. The smallest temperature difference was observed on August 21st 1997 (26.4 versus 24.7°C), with a thermocline at 0 to 2 m depth. The highest pH of the epilimnion of 9 on 6th April 1998 indicated strong al-

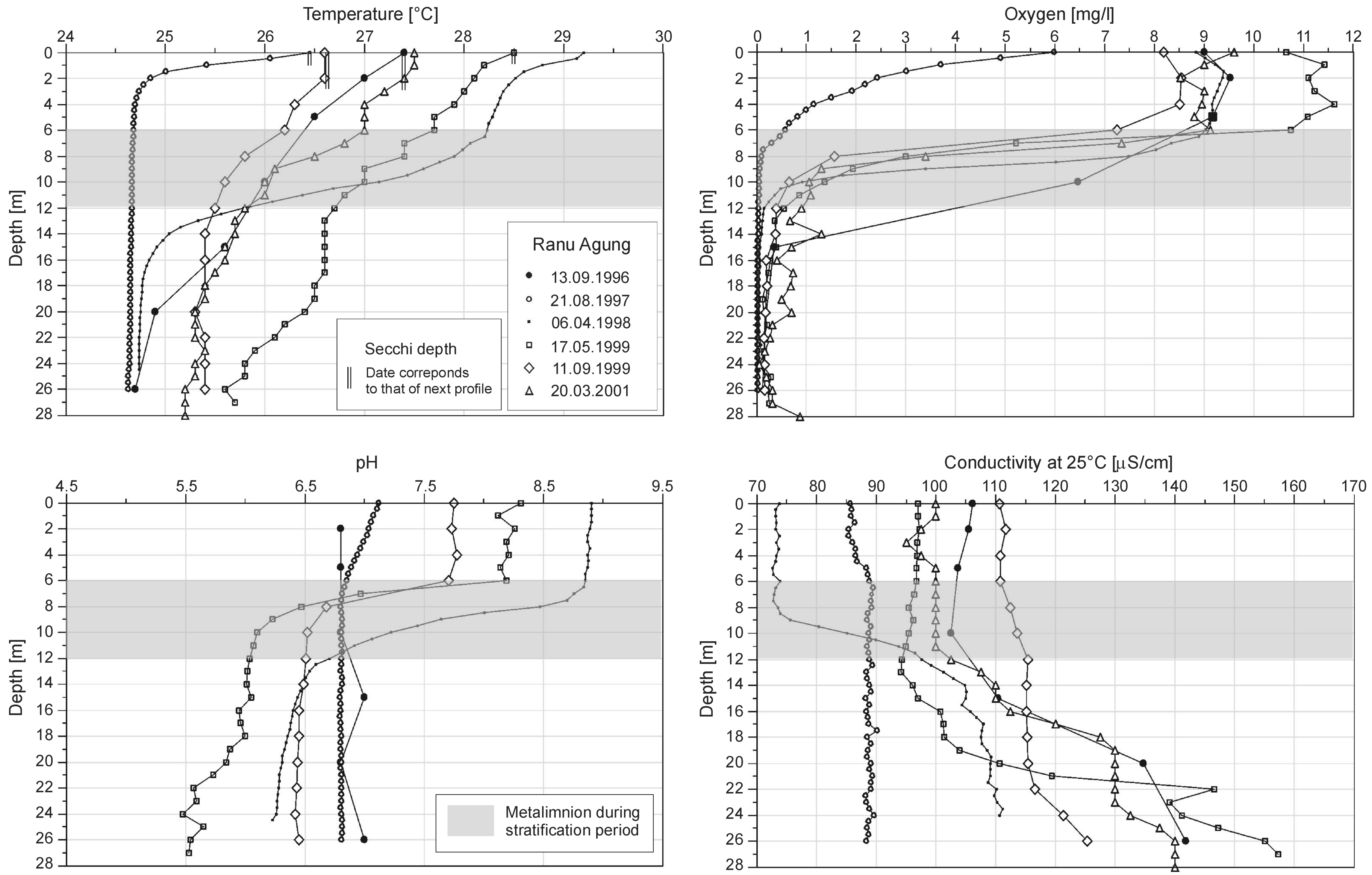

Fig. 6. Physicochemistry of R. Agung. For data from the water sampler we show the original values and those of the CTD (21st August 1997 and 6th April 1998) were interpolated to 0.5 m sampling interval.

gal photosynthesis and eutrophic conditions. On 13th September 1996 and 21st August 1997, no significant variation of the pH was seen versus depth. Oxygen in surface water ranged between 8 and 10.5 mg/l with the exception of 6 mg/l on 21st August 1997, and decreased to values <0.5 mg/l below the thermocline. On 21st August 1997 oxygen was close to 0 mg/l already at 8 m depth. On 20th March 2001 oxygen below 10 m was more irregular than in the other profiles with values up to 1 mg/l including the deepest sample. Conductivity at 25°C varied between 73 and 110 µS/cm at the surface and 85 to 157 µS/cm at the bottom with a general increase below 8 m except for the data from 21st of August 1997 and 11th of September 1999. Stratification was strongest on 6th April 1998. On 17th May 1999, a former partial mixis event was visible from the decrease of temperature above 13 m and below 19 m with constant values between. On 11th September 1999, 13th September 1996 and 20th March 2003, stratification was low to intermediate and it was weakest on 21st September 1997. After Lehmusluoto *et al.* (1995b) it takes at least 3 weeks to establish an oxycline after a mixing event in Indonesian lakes. On 25th September 1997, the lake was green and the visibility was only 110 cm, and fish frequently jumped out of the water for air. Epilimnion was oxygen-poor due to oxygen consumption of microbial activity after holomixis with a diatom bloom. 20 days afterwards the color had changed from greenish to blue and visibility had increased to 140 cm (Theune-Hobbs 1999). From local inhabitants it was reported that green water colors occur once a year for about 15 days, but not always at the same time of the year. This would mean that the lake was monomictic.

Chemical analyses of water samples from 2, 15 and 22 m depth on 21st August 1997 also indicated a shortly preceeding holomixis. They reveal no significant differences between surface and deeper water. The water was rich in hydrogen carbonate (85–92 mg/l) and low in nitrate (<1 mg/l) and phosphate (0.25 mg/l), low in Na (3.8–3.9 mg/l) and K (1.8 mg/l), intermediate in Mg (3.7–5.0 mg/l) and relatively high in Ca (10.2–11.7 mg/l). All analyses from springs around R. Agung document higher cation (46.3–51.5 mg/l) and anion concentrations (135.7–166.9 mg/l) than the samples from the lake (cations 20.8–22.9 mg/l, anions 87.8–94.6 mg/l). Si-content in the springs was 31.0–37.2 mg/l (which is a typical value for basaltic aquifers), about 10-fold that of the lake water with 2.4–3.3 mg/l. The low Si content in the lake water pointed to effective export of Si to the lake sediments by incorporation into diatom frustules.

In September 2003, we observed that during southerly winds a convection cell formed within the deep crater at noon, visible from waves departing from the promontory at the northern shore towards the southern shore line (opposite to the wind direction). When during a cooler period, in July or August, strong monsoon winds come from the east, where the tuff wall is lowest and the diameter of the lake is largest, it is possible that the thermocline breaks down and holomixis is induced by upwelling of deeper, cooler water masses at the eastern side of the lake.

Another mechanism is documented in the varying oxygen content on the 20th of March. The profile was measured after a thunderstorm and the inflow of sediment loaded water from a temporary creek in the northwestern part of the crater. It is possible that the oxygen measured below the thermocline was brought into the hypolimnion by an underflow on the subaqueous part of the alluvial fan, while the thermocline was stable in the remaining part of the lake. This might also be an explanation for anomalously high hypolimnic oxygen values measured on several occasions at R. Klindungan, R. Pakis and R. Lamongan (Sporrer 1995).

When physicochemical data from R. Agung were compared to those of R. Klindungan (Scharf *et al.* 2001) it became evident that the conductivity at 25°C at R. Agung with about 100 µS/cm was much lower than that of R. Klindungan with about 300 µS/cm. This could be a result of the less intensive use of R. Agung by the local population. Reports of massive fish extinctions at R. Klindungan gave evidence of mixing events with upwelling of anoxic hydrogen sulfide-rich waters, occurring at a frequency of about once per 3 months (information from the local population in 2003). If these mixing events resulted in a complete overturn of the water column, R. Klindungan should be considered as an oligomictic lake. A monument and reports about the sinking of 2 amphibian vehicles in 1972 at R. Klindungan pose the question whether a sudden gas eruption might have caused this accident by reducing the buoyancy of the vessels and whether such events have occured repeatedly. If such gas eruptions occured, so far no data have been collected for their impact on the stratification and water quality of the lake. Gas outbreaks might be the reason for the myths linked to this lake.

SEDIMENTOLOGY

Sediments of Indonesian maar lakes have been described by Hummel (1931), Beuning (1996) and Scharf *et al.* (2000, 2001). They consist of partly calcite-bearing diatom gyttja with terrigenous layers. Frequently, a fine bedding or lamination alternates with cm-thick minerogenic intervals that are homogenous or graded.

From 7 investigated lakes in the Lamongan Volcanic Field, sediment cores of R. Segaran seemed to contain the best preserved bedding after macroscopic inspection. In 1999 we collected three sediment cores along a profile from the east to the center of the lake, at 64, 164 and 264 m distance from the shoreline and at water depths of 27.9, 40 and 41.4 m (Fig. 7). Sediments consist of diatom gyttja with graded minerogenic layers. A correlation by means of X-radiographs and magnetic susceptibility is hardly possible between the marginal core, almost lacking a distinct bedding, and the two profundal cores with clearly alternating minerogenic and diatom layers. Basaltic ash, present in all cores between 31 and 32 cm depth, seems to originate from the same ash fall, probably from G. Lamongan. In the central core this 3 mm thick, highly magnetic ash layer is covered by 2 cm of reworked ash, whereas in the other cores the less magnetic ash layer is not covered by reworked ash or entirely mixed with reworked sediment. This is an effect of redeposition of sediments from the proximal to the distal areas. In the proximal profile, two mass flow deposits with low minerogenic content and diffuse top and base are visible at 2–7 and 19–22 cm. Unconformities in the two profundal cores also indicate that the sequence is not complete. To reconstruct a complete pro-

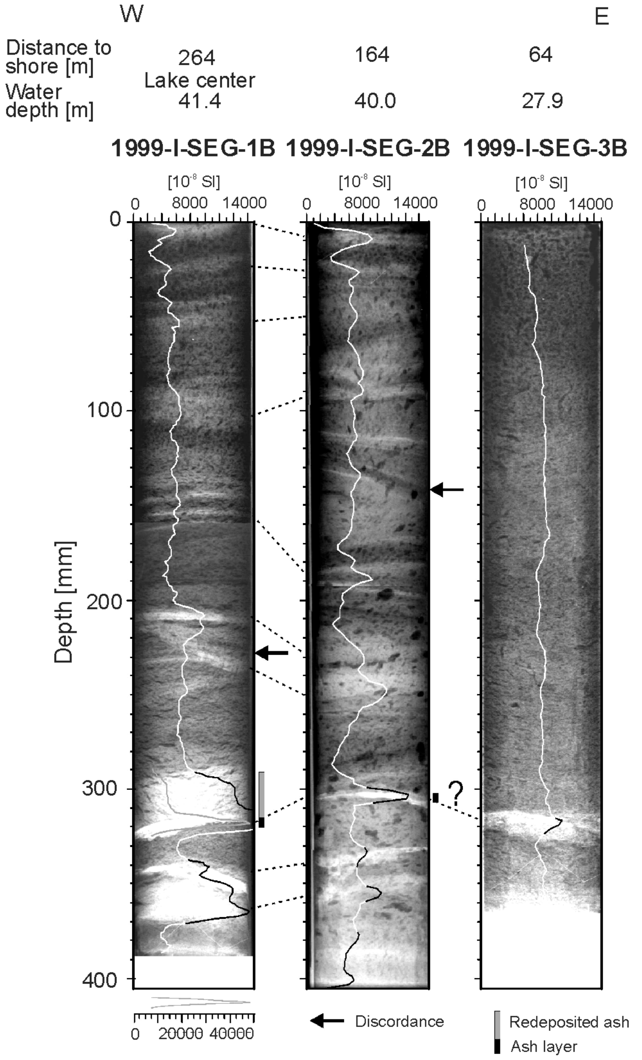

Fig. 7. X-radiographs and magnetic volume-specific susceptibility of sediment cores from a radial profile at R. Segaran (15th May 1999). Density variations seen in the x-radiograph and variations in magnetic susceptibility are caused by differing content of minerogenous and diatomaceous components. An ash layer at 31 to 32 cm depth indicates a possible correlation of proximal and profundal cores.

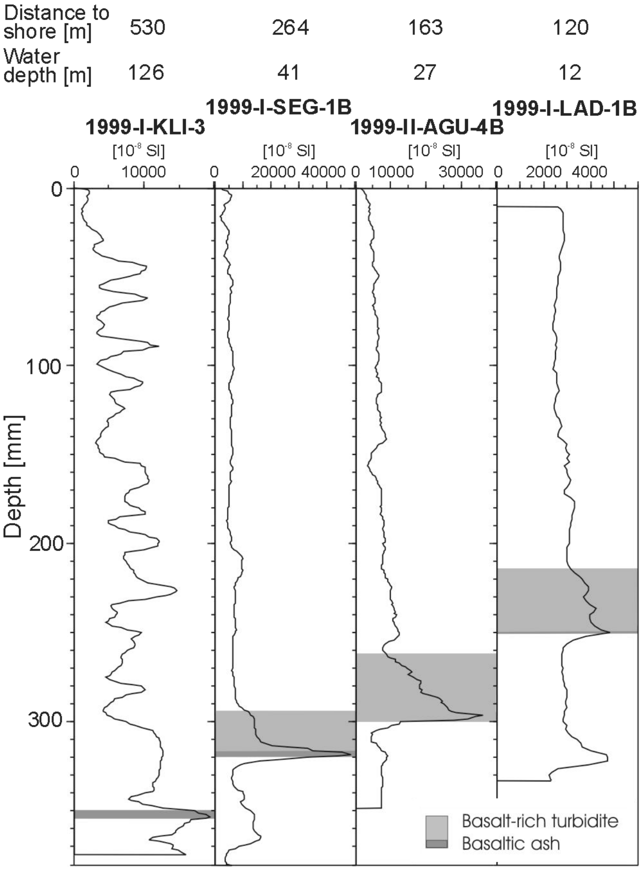

Fig. 8. Volume-specific magnetic susceptibility of sediment cores retrieved in the center of the maar lakes. Peaks of magnetic susceptibility correspond to layers rich in basaltic ash and with high density in X-radiographs. The ash layer in R. Klindungan may be attributed to the 1950 eruption of G. Welirang, 40 km west of R. Klindungan (http://www.info-indo.com/volcano/java18.htm). The ash layer and the redeposited ash in lake R. Segaran, R. Agung and R. Lading in the Lamongan Volcanic Field was deposited by G. Lamongan in 1898 or in an eruption several years before (Carn 2000). The sedimentation rates increase from right to left with diameter and depth of the lakes.

file, more cores from the profundal sediments would be necessary. The sedimentation rates in the lake center are almost equal to more proximal areas. This implies that the area with focussing of the sediments by lateral transport is not restricted to the flat profundal area, but takes place also on the lower part of the subaqueous crater slopes. Turbidites must be a significant factor controlling lake morphology. However, the potential of this lake as a climate archive is limited because of the observed erosional effects of the frequent turbidites.

Another approach to find a lake suitable as a climate archive is the sedimentation rate, therefore we compared profundal sediments of several maar lakes (Fig. 8). The relative variations in the sedimentation rates of R. Lading, R. Agung and R. Segaran sediments are visible by a volcanic ash layer in the lower part of the cores, another ash layer appears in the R. Klindungan sediments. The increase of sedimentation rate with the lake diameter and depth results from a higher input of terrigenous material, whereas sedimentation of biogenous material may be similar in the lakes as the thickness of the epilimnion with high algal productivity is about 5 to 8 m in all the maar lakes during thermal stratification. The higher background values of magnetic susceptibility in the larger lakes indicate a higher contribution of terrigenous material with higher magnetisation whereas in the smaller lakes biogenous material with low magnetisation is less diluted by terrigenous material. Obviously sediment focussing is of higher importance in the larger lakes. Considering the sedimentation rate, R. Klindungan should have a higher potential as a climate archive compared to the lakes in the Lamongan Volcanic Field. This conclusion is supported by the susceptibility signal, that reveals little variations above the ash layer in the cores R. Lading, R. Agung and R. Segaran, whereas strong variations appear in R. Klindungan that indicate an alternation of terrigenous and biogenous layers that reflect environmental changes.

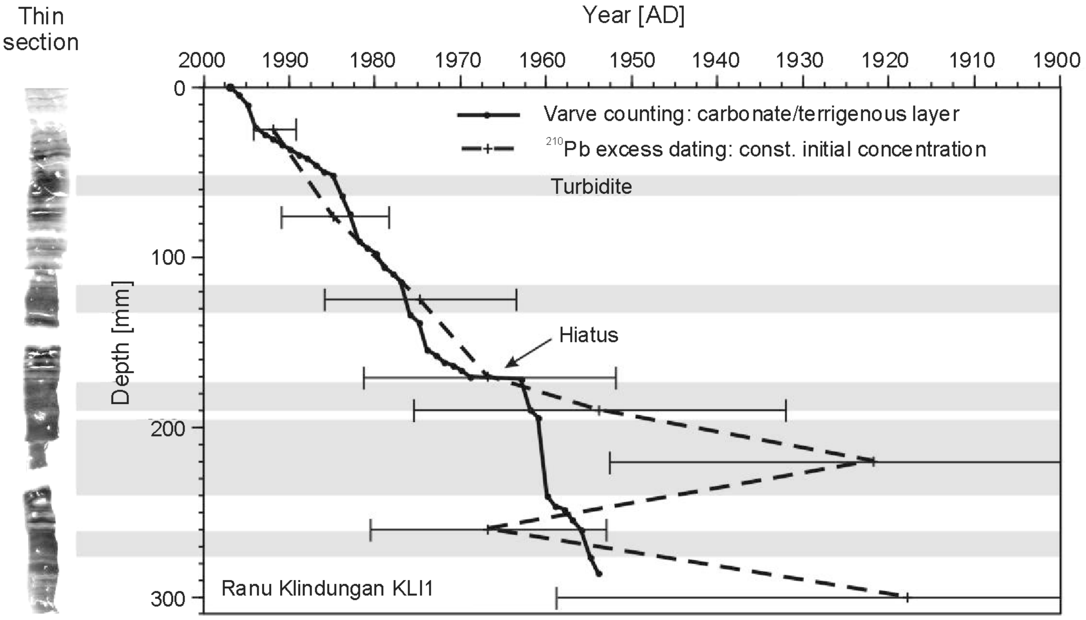

Fig. 9. Age model for core MAJA-1998-I-KLI1, taken at the center of R. Klindungan by B. Scharf (4th April 1998). The varve counting age model is based on the alternance of biogenous and terrigenous layers and corresponds to the ^{210}Pb-excess dating using the Constant Initial Concentration method.

R. Klindungan at the northern slope of the Tengger Massif is the largest maar lake in East Java with a mean diameter of about 1550 m, a max. depth of 126 m, an extended flat profundal lake bottom, and a water table at 16 m a.s.l. (Fig. 4F). On the southern part, towards the Tengger Caldera, the lake is surrounded by an about 50 m high tephra wall whereas towards the north the tephra wall is less than 15 m high or absent. The lake is intensively used for aquacultures and fishing and the water level has been elevated several meters by the construction of a dam in 1861 and 1986. There is a temporary inflow from a small creek and an artificial channel contributing water from a permanent creek on the slope of the Tengger Caldera. In the dry season 2003 the subaerial inflow to the lake was restricted to several springs with a discharge of less than 10 l/s. The outflow was determined on three outlets to irrigation channels on September 13th as 620 l/s. The controlled lowering of the water table during three weeks in September and October 2003 resulted in an apparent outflow of 220 l/s, so the natural outflow can be calculated as 400 l/s. Obviously there must exist a permanent groundwater inflow into the lake. From a comparison of the diatom flora sampled by Hustedt in 1928 and by Burkhard Scharf in 1997/1998 changes of the ecosystem cannot be determined in detail due to taxonomical uncertainties (Scharf *et al.* 2001). The freshness of tephra mined in several open pits and the modest development of erosional grooves on the southern crater wall lead us to assume an age of the volcano in the order of only several thousand years (Scharf *et al.* 2001). Detailed field studies in 2003 revealed, however, that the crater must be older, probably at least some ten thousand years, as the thickness and orientation of the tephra layers indicates that the northern crater wall is buried by late Pleistocene to Holocene sediments of a coastal plain. This is only possible if the crater erupted in a valley during a sea level lowstand, like during the last glacial maximum (18,000 ^{14}C years BP), and was later covered by coastal sediments. The ratio D/d_{crater} of about 11 also implies that the crater should be several ten thousand years old.

The sediments of two cores from the profundal of R. Klindungan have been described in detail in Scharf *et al.* (2001). Based on ^{210}Pb-excess measurements, sediment ages were calculated (Fig. 9) using the Constant Initial Concentration method (Scharf *et al.* 2001). The more frequently used approach to calculate ^{210}Pb-excess ages is the Constant Rate of Supply method (Oldfield, Appleby 1984). This method yields higher ^{210}Pb-excess ages for R. Klindungan sediments compared to ages calculated using the Constant Iinitial Concentration method. Due to the high amount of redeposited older material the Constant Initial Concentration method seems better applicable. Microscopical analyses revealed that one or two diatom and calcite layers are covered by a terrigenous layer (Scharf *et al.* 2001). From the ^{210}Pb-excess ages calculated with the Initial Concentration Method it is plausible that the change from a calcitic to a minerogenous layer is connected to the onset of the rain season in October and that the sediments of R. Klindungan are annually laminated. Then the mean linear sedimentation rate in the 30 cm long core MAJA-1998-I-KLI-1 is 8 mm/yr, with 5 mm/yr for terrigenous and 3 mm/yr for biogenous layers. From thin section comparison with another sediment core it is evident that the biogenous layers in the profundal area are relatively constant in thickness, whereas the terrigenous layers composed of turbidites vary in thickness.

To find out whether magnetic susceptibility can be used as an indicator for climatic variations, we correlated age-scaled magnetic susceptibility of cores MAJA-1998-I-KLI-1 and KLI-3 with monthly means of temperature and rainfall from Surabaya-Perak (WMO station 503969330000), filling gaps in temperature data by data of other sites in Surabaya (WMO stations 9330001, 9330002 and 9330004). Data be-

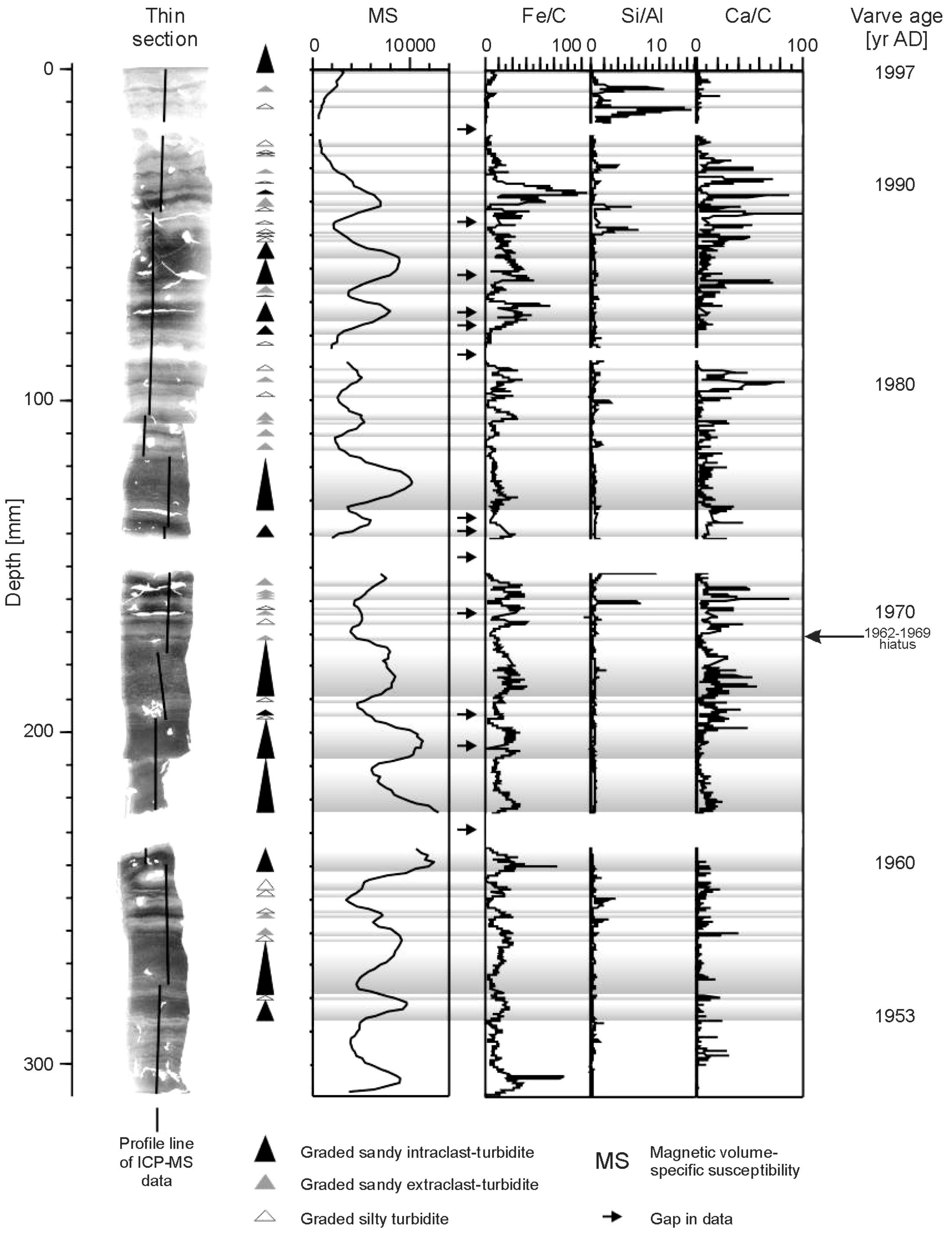

Fig. 10. Sedimentological and geochemical data of core MAJA-1998-I-KLI1. The depths of top and base of turbidites, detected by microscopical analysis, are marked at the position where the turbidites are crossed by the profile line of the ICP-MS-LA data. Peaks of magnetic volume-spec. susceptibility and Fe/C ratios correspond to turbidites, whereas diatom and calcite layers correspond to peaks in Si/Al and Ca/C and low susceptibility.

tween 1951 and 1990 were retrieved from the NOAA database (ftp://ftp.ncdc.noaa.gov/pub/data/inventories). When a 12 month running mean is applied to the temperature data, taking into account the resolution of the susceptibility sensor, temperature is negatively correlated with magnetic susceptibility ($R = 0.52$, $N = 401$), an indication for higher biogenous sedimentation in years with higher temperatures. Between rainfall and magnetic susceptibility no significant correlation exists. This may result from stronger erosion effects during heavy thunderstorms that are not represented by the monthly precipitation values.

On slabs produced for thin sections of core MAJA-1998-I-KLI-1 elemental analysis was performed on an ICP-MS-LA. For the principal composition of the sediments the elemental ratios Fe/C, Si/Al and Ca/C are presented (Fig. 10). From comparison with other element distributions (Al, Si, Pb), and microscopic analyses, it is evident that Fe/C is a measure for the content of terrigenous material. Fe/C peaks correlate with turbidites, that compose about half of the sedimentary sequence. The normal grading of most turbidites corresponds to the upward decrease of Fe/C peaks. Peaks of the Si/Al ratio correspond to diatom layers. More frequent Si/Al peaks towards the top of the core indicate an increase of diatom blooms in the youngest sediments, probably a consequence of eutrophication of the lake by aquaculture. Ca/C corresponds to layers of rhomboedric calcite crystals (on average 40 µm in diameter), probably autochthonously precipitated during algae blooms in the epilimnion. The age of the sediments was not determined by counting peaks of Ca/C below a subsequent Fe/C peak, but from thin section analysis, as intraclasts of diatom and calcite layers occur within turbidites and occasionally produce a similar Ca/C signal as the annual layers (Fig. 10).

When the potential of these maar lakes as climate archive is discussed, the strong human use of the craters has to be considered. Most maar lakes in East Java are used by the local population for fishing, washing of clothes, bathing of working animals, and as a human bath tub. For drinking water only the springs on the inner slopes of the craters are used. At R. Agung, the steep inner slopes of the crater are covered by shrubs and grass. Rare trees are cut for feeding animals. R. Klindungan is the only maar lake which represents a touristic attraction with fishing and boat tours.

During the expeditions to the Lamongan area in 1996, 1997 and 1998, R. Lading was the only maar lake with remains of a jungle vegetation on the steep inner slopes of the crater (Figs. 4B, 4C). Banana and coffee plantations reached the crest of the tuff wall and lake water was pumped up out of the crater for irrigation during the dry season. At the end of the rain season in May 1999, the first trees were cut. Land slides that had occured during the rain season were already covered by new vegetation. This was completely different in September 2003. All trees higher than 2 m have been cut to gain wood for furniture in 2001 (Fig. 4D). In Figs. 4C and 4D the situation in 1999 and in 2003 is presented from a similar viewpoint to show the loss of nearly all trees. First erosion gullies now reach the top of the only sparsely vegetation-covered inner crater wall. Without protection, the future of the lake will be silting up and drying out within the next decade and finally plantations will cover the central crater floor like in the other dry maars around G. Lamongan.

DISCUSSION

Maar craters in East Java are confined to the lower slopes of the Lamongan-Tarub stratovolcano and the Tengger Massif. The crater diameter to depth ratio of several maars in East Java is close to 5, a value that was observed 1981 for the Alaskan Ukinrek East maar that erupted in 1977 (Büchel, Lorenz 1993). At least some of the craters in East Java are less than a few hundred or thousand years old, whereas others with a ratio >11 may be older than 20,000 years.

New depth profiles of physical and chemical parameters combined with published observations (Ruttner 1931, Sporrer 1995, Green *et al.* 1996) support the hypothesis that these maar lakes are monomictic or oligomictic. According to Secchi depths of 90 to 250 cm water quality is different at various maar lakes and temporal changes correspond to the time elapsed since the previous holomixis. More detailed information of the mixing processes, like a longterm monitoring of physicochemical parameters, is required for a better understanding of the limnology of these lakes.

The flat profundal lake floor of all investigated maars indicates that lateral sediment redeposition by turbidites is a common phenomenon in these lakes. At R. Agung, R. Segaran and R. Klindungan turbidites compose about half of the profundal sedimentary sequence. This has not been observed in Holocene maar lakes of the Eifel, but in sediments of Middle Eocene Eckfeld Maar. Probably most of the turbidites are caused by heavy rainfalls of thunderstorms during the beginning of the monsoon rain season, when the vegetation cover, suffering from the preceeding dry season, is less dense.

The 40 cm long sediment cores of several maar craters document environmental changes during the last 50 to hundred years. Of the 8 maar craters studied so far, the best lamination and the highest sedimentation rate is developed in sediments of Ranu Klindungan. If the observed lamination is indeed annual lamination, this lake has a high potential as a tropical climate archive. Whereas lamination is a frequent phenomenon in maar lake sediments, varved sediments of a tropical maar lake have only recently been reported from lake Barombi Mbo in the Cameroon volcanic chain (Giresse *et al.* 1994) and from lake Hora in Ethiopia (Lamb 2001). The reading of this archive, however, is more complicated than in maar lakes of temperate regions because of the high amount of turbidites. With longer sediment cores it would be possible to get information about the environmental history beyond the begin of instrumental meteorological time series on Java.

The example of deforested Ranu Lading demonstrates that these ecosystems should be studied in more detail before further human changes will occur, that might destroy these interesting sites.

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REFERENCES

Assing H. 2001. Geologische, vulkanologische, tektonische und geomagnetische Untersuchungen an drei Trockenmaaren der NW-Flanke des Stratovulkans Gunung Lamongan, Ostjava, Indonesien. Diploma thesis, University of Jena, Jena, 1–87 pp.

Beuning K.R.M. 1996. Modern pollen rain, vegetation and climate in lowland East Java, Indonesia. *Modern quaternary research in Southeast Asia* 14, 1–51.

Brauer A., Endres C., Zolitschka B., Negendank J.F.W. 2000. AMS radiocarbon and varve chronology from the annually laminated sediment record of Lake Meerfelder Maar, Germany. *Radiocarbon* 42, 355–368.

Büchel G. 1993. Maars of the Westeifel. *Lecture Notes in Earth Sciences* 49, 447–465.

Büchel G., Lorenz V. 1993. Syn- and posteruptive mechanism of the Alaskan Ukinrek Maars in 1977. *Lecture Notes Earth Science* 49, 15–60.

Büchel G., Müller C. 1998. Wenn Magma das Wasser explodieren läßt. Die Rolle des Grundwassers bei der Entstehung von Maarvulkanen. *Forschungsmagazin Friedrich-Schiller-Universität Jena* 7, 23–28.

Carn S.A. 2000. The Lamongan volcanic field, East Java, Indonesia: physical volcanology, historic activity and hazards. *Journal of Volcanology and Geothermal Research* 95(1-4), 81–108.

Carn S.A., Pyle D.M. 2001. Petrology and geochemistry of the Lamongan volcanic field, East Java, Indonesia: primitive Sunda arc magmas in an extensional tectonic setting? *Journal of Petrology* 42, 1643–1683.

Giresse P., Maley J., Kelts K. 1991. Sedimentation and palaeoenvironment in crater lake Barombi Mbo, Cameroon, during the last 25,000 years. *Sedimentary Geology* 71, 151–175.

Giresse P., Maley J., Brenac P. 1994. Late Quaternary paleoenvironments in the Lake Barombi Mbo (West Cameroon) deduced from pollen and carbon isotopes of organic matter. *Palaeogeography, Palaeoclimatology, Palaeoecology* 107, 65–78.

Green J., Corbet S.A., Watts E., Lan O.B. 1996. Comparative studies on Indonesian lakes. In Schiemer F., Boland K.T. (eds.), *Perspectives in Tropical Limnology*, 101–111. SPB Academic Publishing, Amsterdam.

Harger J.R.E. 1995. ENSO variations and drought occurrence in Indonesia and the Philippines. *Atmospheric Environment* 29, 1943–1955.

Heublein S. 2002. Fotogeologische, petrografische und geochemische Untersuchungen an den Vulkaniten des Gunung Lamongan, Ostjava, Indonesien. Diploma thesis, University of Jena, Jena, 1–55 pp.

Hummel K. 1925. Vulkanisch bedingte Braunkohlenbildung. *Braunkohle* 23, 293–298.

Hummel K. 1931. Sedimente indonesischer Süßwasserseen. *Archiv für Hydrobiologie Supplement* 8, 615–676.

Lamb H.F. 2001. Multi-proxy records of Holocene climate and vegetation change from Ethiopian crater lakes. Biology and environment: *Proceedings of the Royal Irish Academy* 101B, 35–46.

Lehmusluoto P., Machbub B., Terangna N., Sudarmadji R., Achmad F., Boer L., Brahmana S.S., Bambang P., Setiadji B., Sayuman O., Margana A. 1995. National inventory of the major lakes and reservoirs in Indonesia. General Limnology. *Expedition Indodanau Technical Report* 1–69. Painatuskeskus Oy, Helsinki.

Lorenz V. 1987. Phreatomagmatism and its relevance. *Chemical Geology* 62, 149–156.

Oldfield F., Appleby, P.G. 1984. Empirical testing of 210Pb-dating models for lake sediments. In Haworth, E.Y., Lund, J.W.G. (eds.), *Lake sediments and environmental history*, 93–119. Univ. Minnesota Press, Minneapolis.

Pirrung M., Büchel G., Jacoby W. 2001. The Tertiary volcanic basins of Eckfeld, Enspel and Messel. *Zeitschrift der Deutschen Geologischen Gesellschaft* 152, 27–59.

Ruttner F. 1931. Hydrographische und hydrochemische Beobachtungen auf Java, Sumatra und Bali. *Archiv für Hydrobiologie Supplement* 8, 197–460.

Scharf B.W., Büchel G., Friese K., Mages M., Kunz-Pirrung M., Pirrung M., Schimmele M., Theune-Hobbs M. 2000. Limnological studies on maar lakes in the Eifel area (Germany) and in East-Java (Indonesia) – a comparison. *Terra Nostra* 2000, 445–453.

Scharf B.W., Pirrung M., Boehrer B., Büchel G., Friese K., Kusel-Fetzmann E., Mages M., Treutler H.-C., Witkowski A. 2001. Limnogeological studies of maar lake Ranu Klindungan, East Java, Indonesia. *Amazoniana* 16, 487–516.

Schendel U. 1968. Messungen mit Grundwasserlysimetern über den Wasserverbrauch aus oberflächennahem Grundwasser. *Zeitschrift für Kulturtechnik und Flurbereinigung* 9, 314–326.

Sporrer P. 1995. Vergleichende ökologische Untersuchungen an Seen und Flüssen Indonesiens (Java und Süd Sumatra). Ph.D.-thesis Thesis, University of Giessen, Giessen,1–247.

Theune-Hobbs M. 1999. Hydrogeologische, sedimentologische und vulkanologische Untersuchungen am Ranu Agung-Maar im Lamongangebiet (Ostjava). Diploma thesis, University of Jena, Jena, 1–87.

Trihadiningrum Y., de Pauw N., Tjondronegoro I., Verheyen R.F. 1996. Use of benthic macroinvertebrates for water quality assessment of the Blawi river (East Java, Indonesia). In Schiemer F., Boland K.T. (eds.), *Perspectives in Tropical Limnology*, 199–211. SPB Academic Publishing, Amsterdam.

van Bemmelen R.W. 1970. The geology of Indonesia. – General geology of Indonesia and adjacent archipelagoes. Vol. 1A, 732 pp, Vol 1B: Portfolio. 65 pp. Martinus Nijhoff, The Hague.

van Gerven M., Pichler H. 1995. Some aspects of the volcanology and geochemistry of the Tengger Caldera, Java, Indonesia: eruption of a K-rich tholeiitic series. *Journal of Southeast Asian Earth Science* 11, 125–133.