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RESEARCH ARTICLE

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Detailed investigation of preserved maar structures by combined geophysical surveys

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Abstract The detection of completely preserved maar structures is important not only for underground mapping but also for paleoclimate research because laminated maar lake sediments may contain a very detailed archive of climate history. Objective evidence for the existence of such structures can only be provided by geophysics and boreholes. The combination of gravity and magnetic ground surveys appears to be an excellent tool to detect and identify buried maar structures. Their prominent properties are an almost circular gravity minimum corresponding to a crater filled with limnic sediments of low density, and a magnetic anomaly caused by a pyroclastic or basaltic body in the diatreme which indicates the volcanic character. Seismic measurements provide the most detailed information about the internal structure of the maar sediments. Zones of low seismic reflectivity and very low density represent sediments of the late maar-lake period. The early lake period is indicated by debris flow deposits and turbidites represented by seismic reflectors. The seismic sections clearly reveal the bowl-like structure of the maar. Outside this bowl-like structure, there are only a few reflections, which represent the basement. Taking into account the shape of the gravity anomaly, seismic information allows geometrical modelling of the maar structure. Optimal drilling sites can be selected based on the results of geophysical surveying. Comparing the results of combined geophysical surveys above two maar structures of different ages yields a marked similarity in their geophysical pattern.

Keywords Maar-diatreme · Gravity · Magnetics · Seismic reflection · Borehole geophysics · Messel Pit

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Introduction

The classification of volcanic structures is usually based on visual observations of their shape and structure. Maars are a special type of volcanic structure characterized by circular craters, often filled with water and surrounded by a ring of pyroclastic deposits. They are well described, especially in the Eifel area in Germany, the "home country" of maars (Schmincke 1988; Büchel 1993). Lakes are common in these craters, and they may be gradually filled with sediments. The surface morphology of maar structures is changed by erosion and compaction, or is hidden by younger sediments. Discovering hidden maar structures is not only important for clarifying the geological structure itself, but also for paleoclimate research because the fine lake sediments may preserve a very detailed archive of climate history.

Completely preserved maar structures are restricted to areas of subsidence. Therefore, evidence for their existence can only be based on geophysics and boreholes. Gravity and magnetics are the most common geophysical methods for prospecting maars (e.g. Wood 1974); Quaternary dry maars in the Eifel area and some Tertiary maar structures in the German highlands have been investigated by gravity and magnetic methods (Büchel 1993; Pirrung et al. 2003). Tóth (1992) also included the resistivity method to detect hidden maars in the Slovakian Basin (Puchnerová et al. 2000). However, none of these methods give any information on the internal structure of the maar-lake sediments. The different sedimentary layers can only be imaged by seismic reflection methods. High-resolution seismic techniques have been used in lakes to investigate sedimentary layers, for example, in a recent maar lake in Latium, Italy. The maximum penetration was 35 m and the vertical resolution some decametres (Niessen et al. 1993). In this paper, we show the results of high-resolution reflection seismic survey over completely covered maar-lake sediments down to 500 m and a vertical resolution of several meters. Combined geophysical surveys, including gravity and magnetic surveys, reflection seismic, borehole logging, and laboratory investigations, provide new insights into the maar structure and its genesis.

Maar structure

Phreatomagmatic eruption mechanisms and the geology of maar-diatreme structures have been discussed comprehensively in several papers (e.g. Fisher and Schmincke 1984; Lorenz 1986; Lorenz et al. 2003; Pirrung et al. 2003; Wohletz and Zimanowski 2000; Zimanowski and Wohletz 2000). Phreatomagmatic explosions result from short-term, near-surface magma/water interactions. The thin, heat-insulating vapor film existing between the two phases (Leidenfrost phenomena) breaks down. In a fraction of a second, vapor is generated which creates an explosion chamber due to hyperbaric pressure. This fragments the surrounding country rock. The contents of the chamber are ejected through a vent towards the Earth's surface and generate a tremendous eruption plume. The explosion cavity is filled by breccias. Generally, a series of explosions follows the first one. These excavate the explosion site and produce a complex zone of breccia with an irregularly shaped root zone. The initial diatreme is formed. Collapse of the surrounding and overlying rocks fills the root zone with breccias. The collapse structure propagates to the surface resulting in the formation of the initial maar crater (Fig. 1). As long as meteoric water or groundwater is available, a lake is created and sediments are deposited in the maar crater.

An attempt to generalize the lithofacies of maar structures in the German highlands was published by Pirrung et al. (2003). They defined five lithozones describing the sedimentation during typical stages of maar formation within the diatreme structure and the maar crater (Fig. 1):

Diatreme structure

- lithozone A: Diatreme breccia
- lithozone B: Syn-eruptive collapse breccia (first sediments to be deposited after eruptions cease)

Crater sediments

- lithozone C: Debris flow deposits and turbidites (sedimentation of the early lake period)
- lithozone D: Laminated sediments with interbedded turbidites (sedimentation of the stabilised lake period). This zone is divided in 4 subzones, from D1 at base to D4 at top, depending on the content of turbidites:
  - lithozone D1: Dominated by irregularly spaced thick turbidites (bed thickness up to several meters); turbidites make up between 50% and 100% of the sediments.

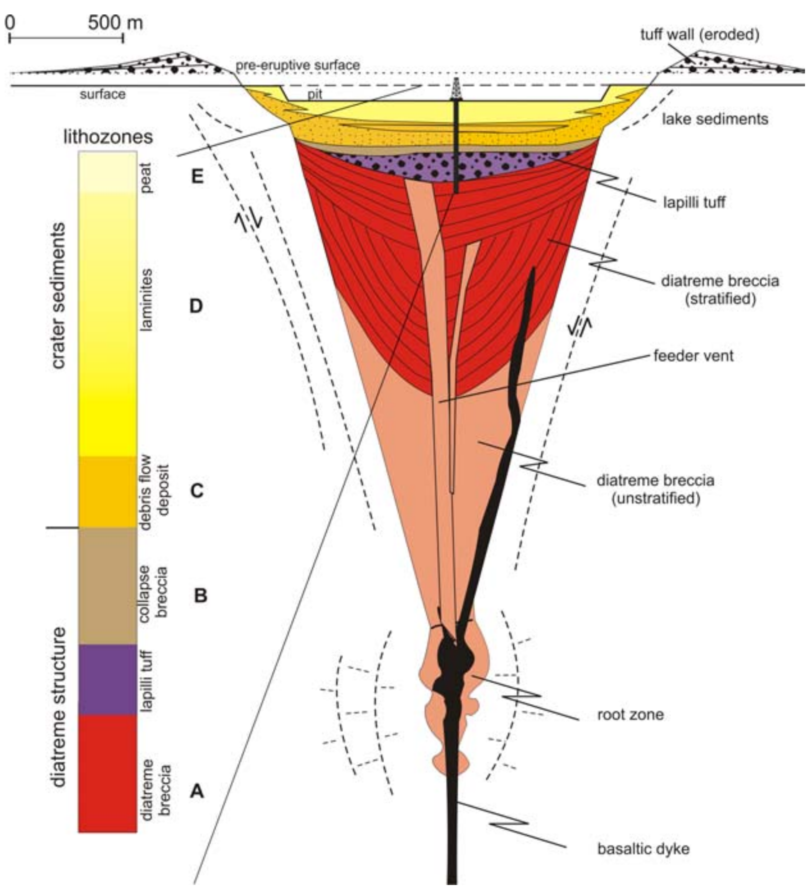


Fig. 1 Diagram of a maar-diatreme structure (after Lorenz 2000), modified for the Messel pit by Felder and Harms (2004); no exaggeration. The lithozones after Pirrung et al. (2003) are not to scale

  - lithozone D2: The abundance of turbidites increases; their content (ca. 50%) decreases because discrete beds are thinner (down to 1 mm).
  - lithozone D3: Turbidites are nearly absent.
  - lithozone D4: Typical delta sediments, with clay as bottomset beds and sands as foreset beds.
- lithozone E: Peat (silting period of the maar lake); topset beds of the delta sedimentation.

Study areas

The study areas (Figs. 2 and 3) comprise two locations in Germany where structures are now unambiguously determined by boreholes as maars: the Baruth maar, Saxony, and the Messel Pit, Hesse.

Baruth maar

Most volcanic rocks and phreatomagmatic structures in Saxony, Germany, are related to the Ohře Rift (Eger Graben) in the Czech Republic, and the associated cross faults (Ulrych et al. 1999). The volcanic units are dated from the Middle Eocene (approximately 40 Ma) to the Middle Miocene (14.7 Ma). The main phase of volcanic activity was from Late Oligocene to Early Miocene (between 28 and 20 Ma) (Goth et al. 2003). In addition to effusive eruptions, phreatomagmatic eruptions also occurred during the main period of volcanism. This activity created craters that were subsequently filled up with maar-lake sediments and covered by Tertiary sediments. The Kleinsaubernitz structure (Suhr 1999) as well as the Baruth maar (Goth et al. 2003; Lorenz et al. 2003) are the result of such a development (Fig. 2).

Messel Pit

The Messel Pit (Fig. 3) near Darmstadt (Hesse, Germany), located only 6 km east of the eastern Rhine Graben rim, is a deposit of Middle Eocene sediments within the Paleozoic fault block of the Sprendlinger Horst (Schaal and Ziegler 1992; Harms 2000). It is one of the most important localities worldwide for fossils of animals, especially mammals, and plants. For this reason, the UNESCO declared the Messel Pit a World Heritage Site in 1995. Between 1859 and 1971, oil shale was mined resulting in an excavation 60 m deep and 750 m in diameter. The rock is a very dark, finely layered claystone, rich in organic material. Despite good knowledge of this oil shale pit, the genesis of the Messel structure was largely unknown. Three hypotheses have been discussed in the literature for more than 100 years: a volcanic structure, a pull-apart basin connected with the Rhine Graben tectonics, and an impact structure. Geophysical investigations, described in this paper, and a research drilling program, carried out in autumn 2001, revealed that the basin was created 47 Ma ago by phreatomagmatic explosions (Schulz et al. 2002).

Geophysical surveys

Potential field methods

Preserved maar-diatreme structures normally cause a significant gravity low due to the large density contrast between the lacustrine sediments and the surrounding rock (e.g. Büchel 1993). Such structures become visible in regional gravity surveys only if the diameter of the maar is much larger than the measuring grid or if a gravity point is coincidentally located above the maar structure.

A nearly circular local gravity minimum was observed in the vicinity of Baruth, Saxony. A detailed gravity survey

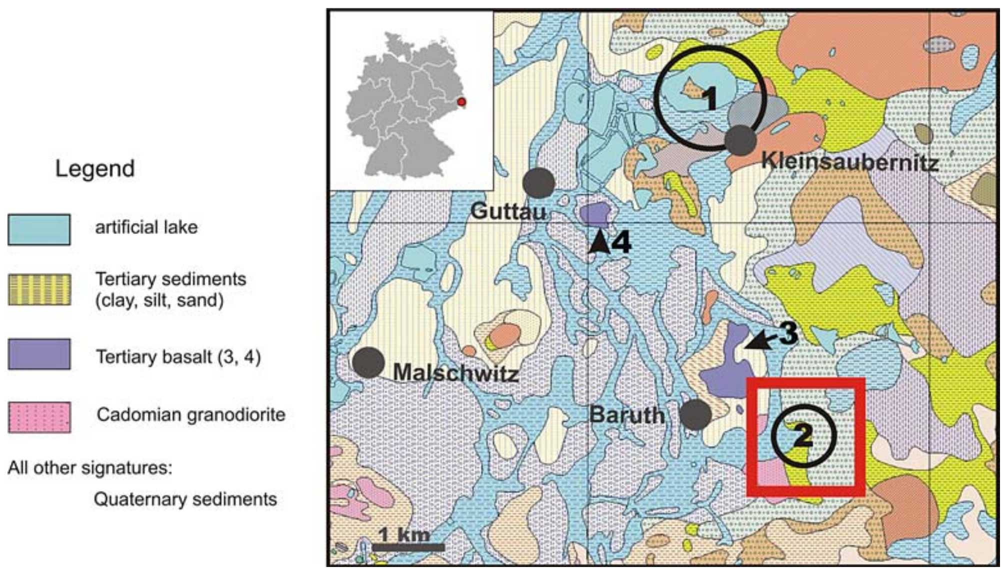


Fig. 2 The Baruth area: Detail of the geological map of the areas of Saxony covered by Pleistocene ice (Standke 1999). Nos. 1–2 are hidden maar structures, visible neither in the geological map nor in topography; Nos. 3–4 are volcanic structures. The study area (cf. Fig. 4 left) is marked by a rectangle

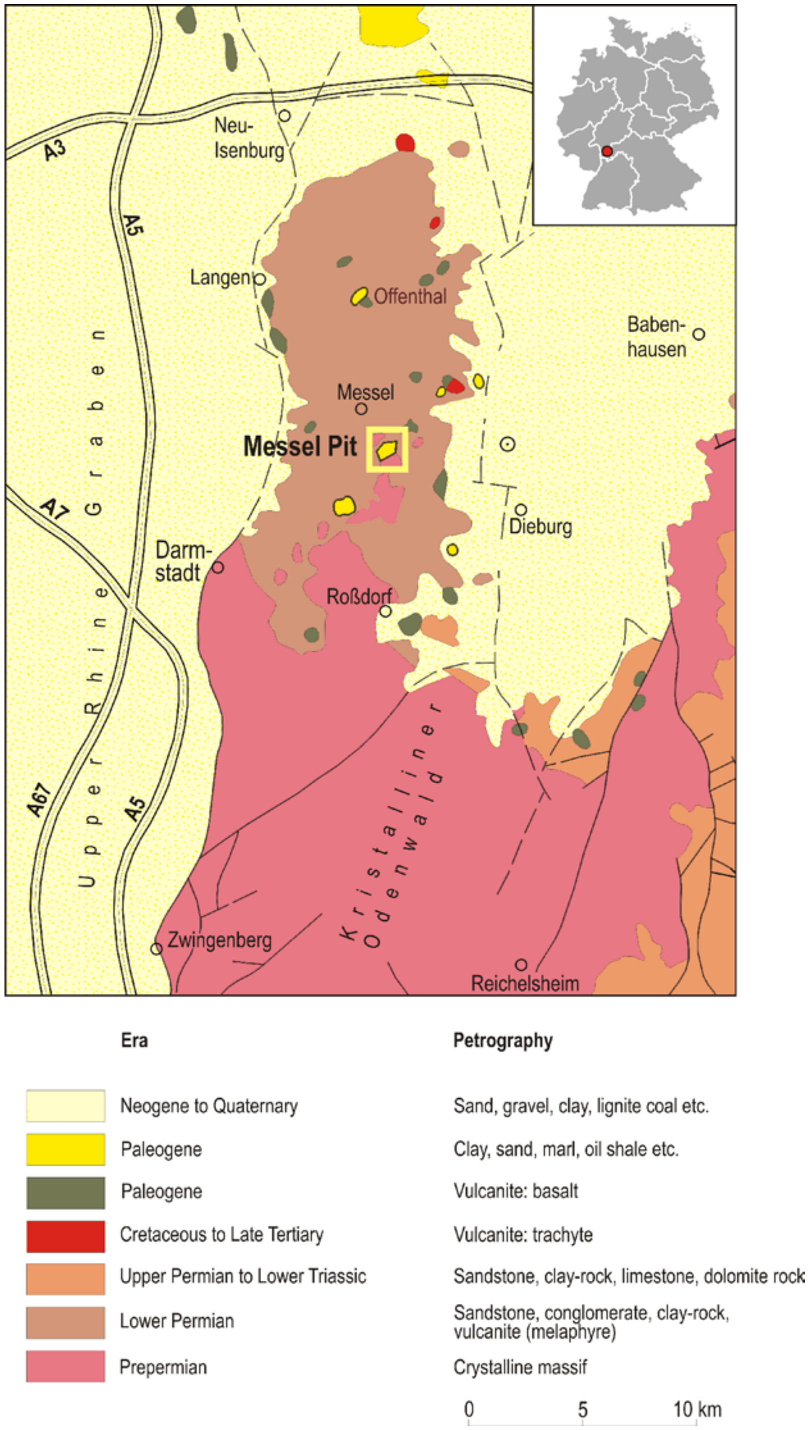


Fig. 3 The Messel area: Geological tectonic survey map of the Sprendlinger Horst (Harms 2000). There are some small depressions (diameter less than 1 km) with Middle Eocene sediments. The study area (cf. Fig. 4 right) is marked by a *rectangle*

was carried out to determine the depocenter of the lacustrine sediments in the Baruth structure. A total of 434 gravity measurements were made, covering an area of 2×2 km. The resulting Bouguer anomaly (Fig. 4, left), based on I.G.S.N.71 and a reduction density of 2,670 kg/m^3, shows a nearly circular anomaly of -6.6 mGal with a diameter of approximately 1,100 m superimposed on the regional NE–SW gradient. The circular shape of the anomaly is the first piece of evidence indicating a maar-diatreme structure. The half-width of the gravity anomaly provided an estimate of the depth of the expected lacustrine maar sediments: a maximum depth of 400 m is obtained by approximating the maar by a vertical cylinder. The point of gravity minimum was chosen as the optimum location for the Baruth 1/98 borehole.

Magnetic measurements were performed in the Baruth area along several E-W profiles with a profile spacing of 100 m and a point spacing of 20 m. A positive magnetic anomaly was detected. The amplitude of the nearly circular anomaly is 320 nT, its diameter is about 600 m (Fig. 4, left).

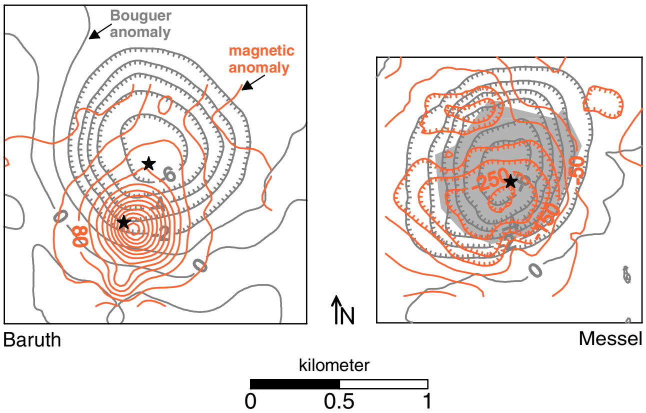


Fig. 4 Bouguer anomaly (*grey*, contour interval 1 mGal) and anomalies in the total magnetic field (*brown*, contour interval 20 nT for Baruth area and 50 nT for Messel area) of Baruth and Messel (after Jacoby et al. 2000). The locations of the Baruth 1/98 and Baruth 2/98 boreholes and the Messel 2001 borehole are marked by a *star*; the mined area of the Messel Pit is shaded *grey*

The centre of the magnetic anomaly does not coincide with the gravity low but occurs about 500 m to the south. This anomaly extends with decreasing values to the centre of the gravity anomaly in the north. If the source body has a regular geometrical shape, a small magnetic kidney-shaped minimum (about 10% of the maximum value) north of the maximum would be expected at the latitude of the location (51°N), but this is obviously not the case. The regular shape of the magnetic anomaly indicates a source body deep enough to prevent body irregularities affecting the anomaly isolines. The gravity contour lines do not show any deformation in the area of the magnetic anomaly. Therefore, a basaltic body with higher density cannot be embedded in the sediments with low density; the magnetized body has to be assumed to lie within the country rock with similar densities. The modelling results are described below.

Regional structures have a much stronger influence on the gravity field in the Messel area than they have in the Baruth area. Thick sediment layers of the Rhine Graben to the west and Palaeozoic rocks of the Odenwald to the south (Fig. 2) cause strong gravity gradients (Plaumann 1991). Therefore, special attention was paid to a precise observation of the regional gravity field; supplementary gravity measurements in addition to the existing regional database were carried out within a radius of 10 km around the Messel Pit. Local gravity and magnetic surveys within the Messel Pit were carried out by the geophysics group of Mainz University (Jacoby et al. 2000). Due to the rough topography of the pit, the distribution of gravity points is less regular than in the Baruth area. A digital elevation model with 40-m grid spacing provided by the ordnance survey was used for the terrain reduction; it was completed by additional height measurements (Jacoby et al. 2000) in the area of the Messel Pit. The residual gravity anomaly was calculated as the difference between the two grids. The first one is based on all gravity data including 160 gravity stations in the Messel Pit, whereas the second one includes the regional data only. The result (reduction density 2,670 kg/m^3) is a negative residual anomaly of −7 mGal with an elliptical shape (Fig. 4, right).

As for the gravity data, the distribution of magnetic data is limited by the topography and by anthropogenic disturbances due to industry at the north-western rim of the Messel Pit. After removing spurious data, the resulting magnetic anomaly is nearly circular with a diameter of 1,000 m and an amplitude of about −320 nT (Fig. 4, right).

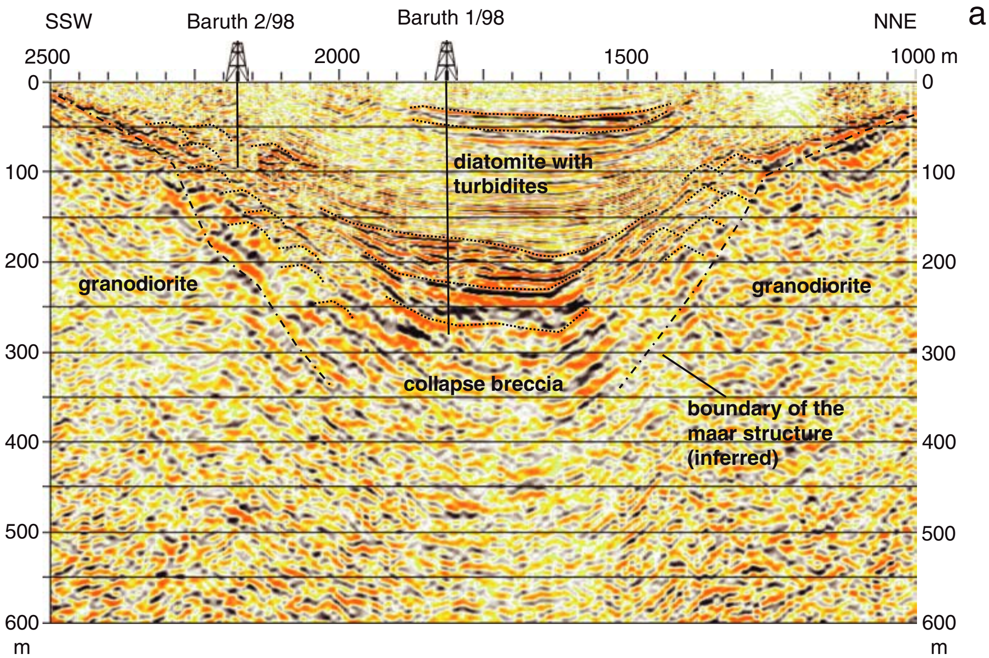
The diameter of the elliptical residual gravity low at Messel is about 1,500 m in a N–S direction and 1,100 m in an E–W direction. As at Baruth, the location of the absolute gravity minimum was chosen for the drilling site. The centre of the magnetic anomaly is located about 200 m south of the centre of the residual gravity field. In contrast to Baruth, the magnetic anomaly at Messel is negative. Such a negative anomaly could be explained by the effect of a hole in a positive magnetized plate; however, 3-D magnetic modelling shows that this model approach is unable to explain the shape of the observed anomaly. Therefore, a source body with negative magnetization has to be expected below the nearly non-magnetic limnic sediments of the former maar lake. The source body preserves an inverse remanent magnetization, obtained at a time of reversed Earth's magnetic polarity.

Seismic reflection data

Based on the information provided by the gravity surveys, seismic measurements were carried out in both study areas. The measurements in the Baruth area took place along two perpendicular 2-D reflection seismic lines with the point of intersection near the centre of the gravity minimum. A total of 336 shot points with the SISSY seismic impulse source system (Wiederhold et al. 1998) resulted in a common-midpoint (CMP) section 4.25 km long with CMP spacing of 5 m and 24-fold CMP. This seismic configuration allows a simple approach to 3-D interpretation (Wiederhold 2005).

The bowl-like Baruth structure is clearly revealed by reflections from its sedimentary fill (Fig. 5a). Outside this bowl-like structure, there is only one reflection event with coherent signal energy in the depth range down to 40 m, which represents the granodioritic basement. Additionally, resistivity measurements were made in the Baruth area along the seismic lines using Schlumberger half arrays with a maximum spacing of 3,000 m. The interpretation of the sounding curves leads to a 2-D model of the maar (Rodemann and Worzyk 2000). As expected, the results of 3-D resistivity imaging confirm the structure of the maar (Brunner et al. 1999) without yielding a more detailed image of the internal maar structure.

At the Messel site, the layout of the four seismic lines was hampered by the strong relief left by opencast mining. Therefore, the lines are only 600 m long, and merely show part of the whole structure. The limited length resulted in a fixed spread layout with geophone and source distances of 5 m. A small hydraulic vibrator developed by the GGA-Institute (Buness and Wiederhold 1999) was used as the seismic source. The geological interpretation of the seismic



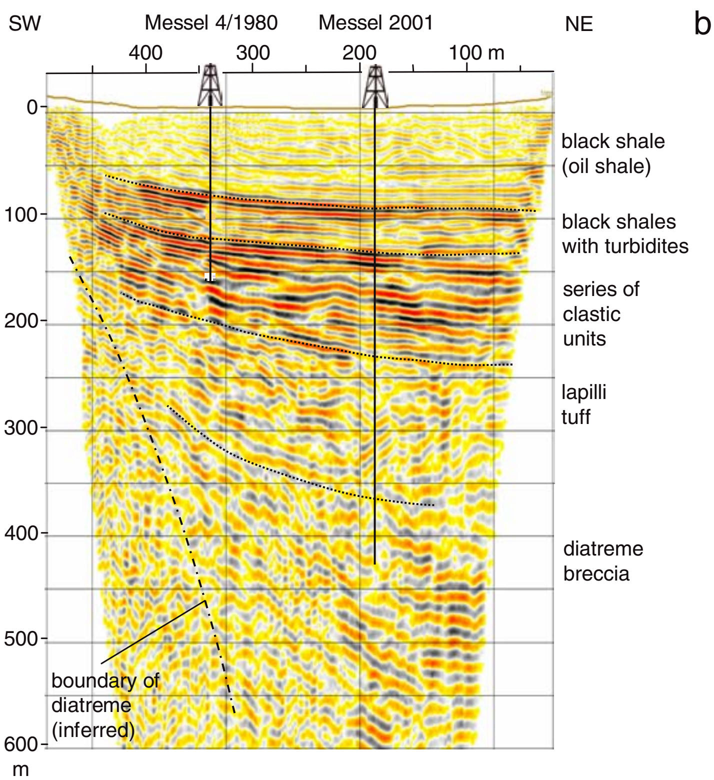
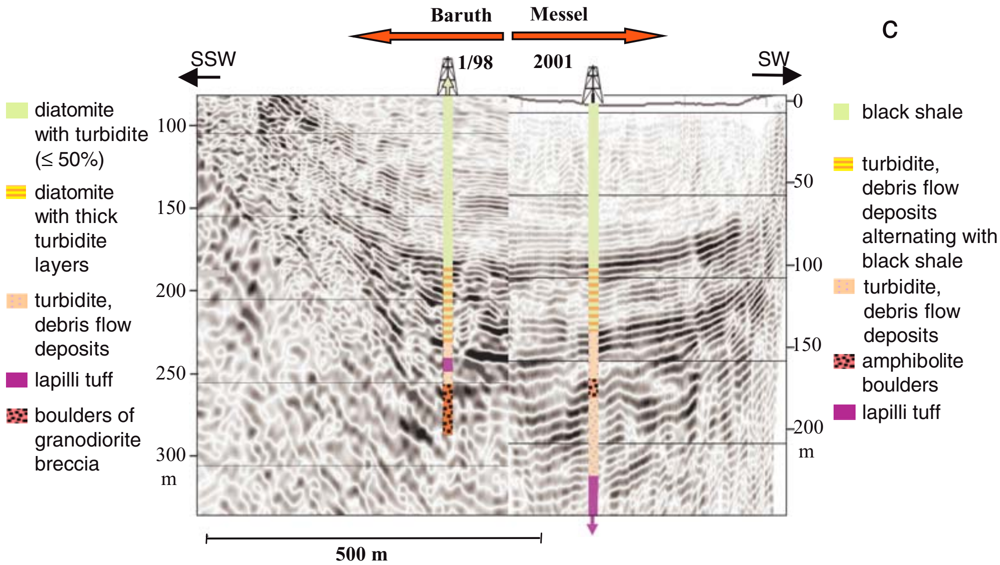


Fig. 5 **a** Seismic line crossing the maar structure at the Baruth site (vertical exaggeration approximately 1.5). Positive amplitudes are displayed in *red*, negative in *black*. The bowl-shaped structure of the former maar is clearly recognizable, as well as the top of the granodiorite units at the edges. The *small dotted arches* at the edge of the maar denote granodiorite. In the vicinity of the Baruth 1/98 borehole, the uppermost 36 m consist of post-maar Tertiary sediments, the diatomite layers start at a depth of 50 m. The collapse breccia below the lake sediments is reached at 257 m depth. **b** Seismic line at the Messel pit (no vertical exaggeration). Due to the rough topography, only part of the maar structure can be shown. The black shale unit on top continued for another 55 m before the start of opencast mining. The lithological units can be differentiated (*dotted lines*) because of their varying reflectivity. **c** Comparative display of the seismic sections at Baruth (*left*) and Messel (*right*). A strong similarity in the reflection patterns is obvious. The sections are shifted 90 m with respect to one other to compensate for the Tertiary cover of the Baruth maar and the mining of maar sediments at the Messel pit. The depths refer to the boreholes, which are shown with a generalized lithology after Goth et al. (2003), and Felder and Harms (2004)



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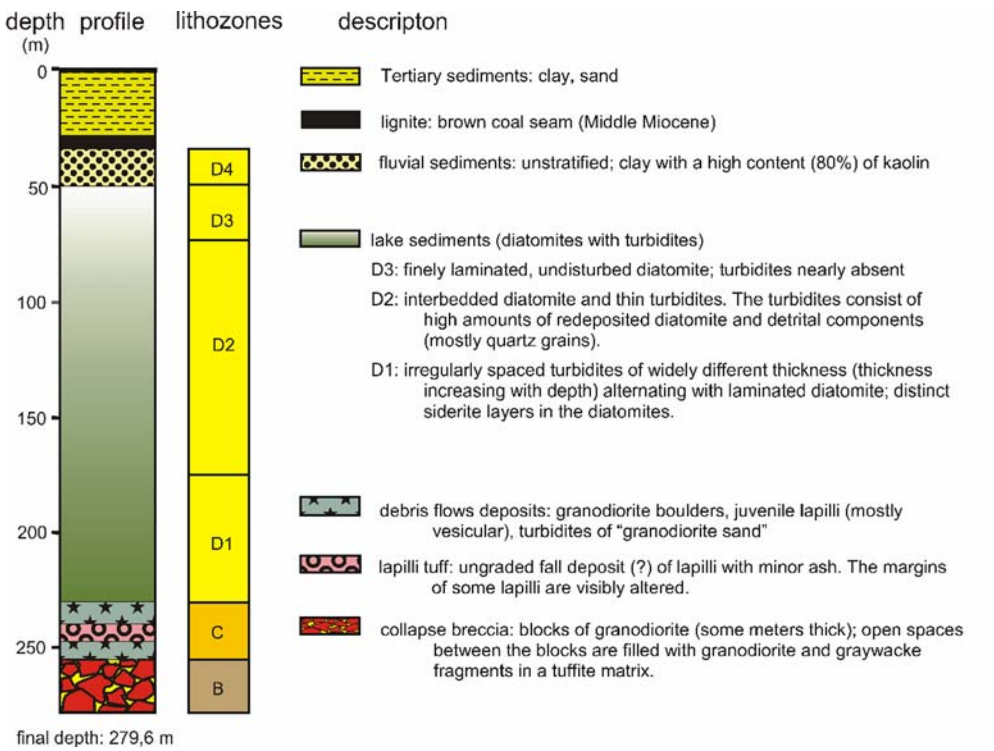

Fig. 6 Baruth 1/98 borehole: Lithological log, lithozones and description after Goth et al. (2003)

sections (Fig. 5b) is based on the results of numerous shallow boreholes in the Messel Pit and, for depths greater than 150 m, the Messel 2001 borehole (Felder and Harms 2004).

Petrophysical properties of the maar fillings

The Baruth maar

On the basis of the geophysical results, two research boreholes were drilled in the Baruth area in 1998 (Goth et al. 2003) and one borehole in the Messel Pit in 2001 (Schulz et al. 2002).

The Baruth 1/98 borehole (279.6 m deep; Fig. 6) was drilled close to the centre of the gravity anomaly with the aim of cutting a complete section of the lacustrine sediments; the Baruth 2/98 borehole (100 m deep) was drilled near the maximum of the magnetic anomaly. Geophysical logging of the boreholes revealed important geological and physical details (Table 1) of the maar-lake sediments. The laminated sediments show anomalous physical properties, and in particular a very low density (1,400 kg/m^3 or less -

Table 1 Mean values or ranges of petrophysical properties of maar-lake sediments (lithozones E/D/C) and diatreme structure (lithozones B/A) measured in the Baruth 1/98 borehole; lithozones according to Pirrung et al. (2003); n. m.: not measurable (because of casing)

Lithozone rock	Depth (m)	Thickness (m)	Density (kg/m)	Velocity (VSP) (m/s)	Gamma ray (API)	Susceptibility (10^{-4} SI)	Resistivity (Ωm)
E	Eroded						
D4	36–50	14	1,800	n.m	30	n.m	30–100
D3	50–74	24	1,350	1,500–1,600	40	<1	10–25
D2	74–186	112	1,500	1,500–1,600	55	1	10
D1	186–232	46	1,200–1,900	1,800–2,400	60	5–80	10
C	232–240/248–257	17	2,100	2,500	80	10	10
Lapillituff	240–248	8	1,500–1,800	3,000	40	9	3–12
B	257–280	>23	2,600–3,000	3,500	120	1.5–100	2,000
A	Not reached						

the higher the proportion of diatomite, the lower the density) and low seismic *P*-wave velocity (1,600 m/s) derived from a vertical seismic profile (VSP).

The seismic sections in the Baruth area (Fig. 5a) can now be lithologically interpreted by means of cores and borehole logging (Fig. 6). Reflections down to 50 m correlate with Middle Miocene sediments (clay and sand, 0–32 m), a brown coal seam (32–36 m), and sand (36–50 m, lithozone D4) indicating fluvial deposits. During the sedimentation of the stabilised lake period, diatomite was deposited (50–232 m, lithozone D3-D1); the proportion of interbedded turbidites increases with depth. In the upper part (50–74 m, lithozone D3), turbidites are nearly absent, therefore the density is extremely low (mean value 1,350 kg/m^3) and there is no seismic reflectivity. The depth range down to 186 m (lithozone D2) is relatively poor in reflections except for a strong, very high-frequency seismic signal at about 140 m that represents phonolitic ash layers. Poor reflections correlate with turbidites. The abundance of turbidites decreases towards the bottom, whereas their volume increases due to the greater thickness of the discrete beds.

Reflections in the depth range from 186 m to 232 m (lithozone D1) correlate with diatomite horizons alternating with thick turbidite layers. The base of this lithozone is a good seismic reflector due to the strong density contrast (1,400 to 2,100 kg/m^3). Debris flow deposits and sand are evidence for the early stage of limnic sedimentation (232–257 m, lithozone C). This facies causes strong low-frequency seismic signals. In the deepest part of the borehole (257–280 m), boulders of granodiorite breccia were found. The petrophysical properties of this collapse breccia, i.e. the first sediments after the end of the eruptions (lithozone B), depend on the rock surrounding the diatreme. If the original rock is granite, granodiorite or amphibolite, the resistivity is high (sometimes greater than 2000 Ωm), the density is normal to high (2,600 kg/m^3, up to 3,000 kg/m^3), and the interval velocity is high (up to 3,500 m/s; Table 1).

The Messel Pit

The Messel 2001 borehole (Fig. 7) was drilled close to the gravity and magnetic minima to cut through a complete section of the remaining maar sediments and to penetrate the magnetic source body. The petrophysical properties are listed in Table 2. One of the most striking features in the seismic section (Fig. 5b) is the absence of distinct reflectors in the uppermost part of the section. This feature can be seen on all seismic sections, showing that the organic-rich claystone (black shale, so-called oil shale) lacks strong reflectors; this zone reaches a maximum depth of about 100 m (lithozone D3/D2). A strong and continuous reflection at that depth represents the top of a thin clastic layer (sand, clay, gravel) and is defined as the base of a formation which consists of pure black shales. The weakly reflective shales dominate for another 40 m (lithozone D1), where again strong reflectors mark its base. The underlying strong reflectors, some of them continuing along the line, correspond to a series of clastic subaquatic infills (143–228 m, lithozone C) with strong variations in particle size. At their base, the sediments are dominated by sand, clay, and gravel, interbedded with tuffs and breccias. Black shales are absent. A significant change in the sediment colour at 229 m depth indicates the beginning of the subaquatic sedimentation of the former maar lake. The disappearance of strong reflectors at a depth of 240 m in the central part marks the bottom of the maar crater. The thick layer of lapilli tuff (240–373 m) is definitive evidence for the volcanic origin of the structure (Felder and Harms 2004). It is distinguished by very high magnetic susceptibility and shows a distinctly weaker reflectivity (Table 2). The thick tuff layer contrasts with the lapilli tuff found in the Baruth 1/98 borehole (240–248 m) which is interbedded with the sediments of the early lake period. This interstratification implies that the tuff of the Baruth borehole did not originate from eruptions of the Baruth maar, and are probably fall deposits erupted from a separate vent (Goth et al. 2003).

In the Messel borehole, the layered breccia of the diatreme (lithozone A) was found from 373 m down to the bottom of the hole at 433 m; each layer (thickness between 5 m and 20 m) is dominated by one type of clast. These stratifications cause prominent reflectors. At depths of 450–550 m, horizontal as well as dipping (30–40°) reflectors appear, indicating layering in the breccia.

Table 2 Mean values or ranges of petrophysical properties of maar-lake sediments (lithozones E/D/C) and diatreme structure (lithozones B/A) measured in the Messel 2001 borehole; lithozones according to Pirrung et al. (2003)

Lithozone rock	Depth (m)	Thickness (m)	Density (kg/m)	Velocity (VSP) (m/s)	Gamma ray (API)	Susceptibility (10^{-4} SI)	Resistivity (Ωm)
E	Mined/eroded						
D4	mined						
D3	0–28	>28	1,400	1,600	50	1	20
D2	28–94	66	1,500	1,600	55	1	20
D1	94–143	49	1,200–1,700	1,600	60	1	10
C	143–228	85	1,500–2,500	1,800–3,500	50–100	1–800	20
B	228–240	12	2,200	2,000	80–120	1–50	15
Lapillituff	240–373	133	2,200–2,400	2,700–3,000	100–120	100–300	16
A	373–433	>60	2,000–3,000			1–100	
Granodiorite			2,900	5,500	<20		till 2,500
L. Permian			2,200	4,500	100–120		50

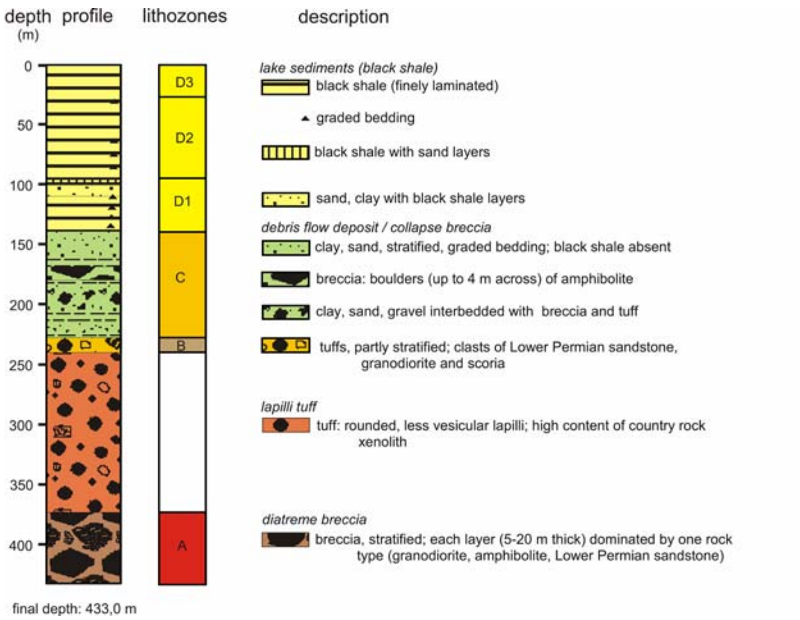

Fig. 7 Messel 2001 borehole: Lithological log, lithozones and description after Schulz et al. (2002), and Felder and Harms (2004)

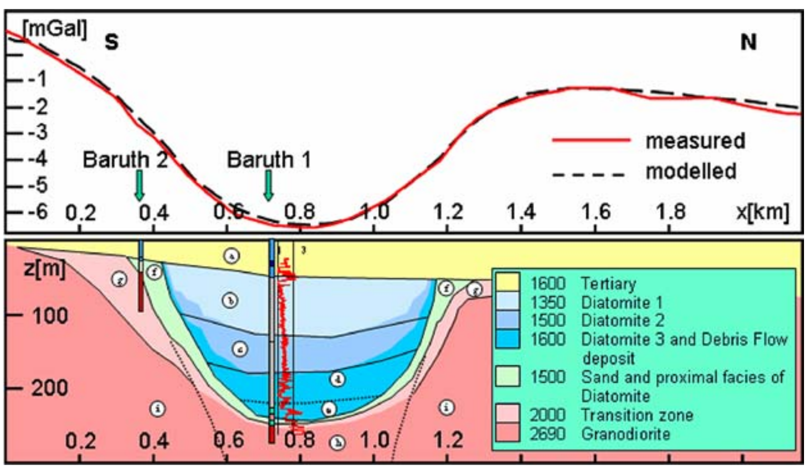

Fig. 8 Top: Measured (*red solid line*) and calculated (*black dashed line*) gravity values along a representative section across the buried maar near Baruth. Bottom: Corresponding cross section through the three-dimensional gravity model. The Baruth 1/98 and Baruth 2/98 boreholes are shown, as well as the Baruth 1/98 density log. The modelled density distribution is *coloured*, the density is given in kg/m. Interpreted lithological boundaries with density contrasts are represented by *solid lines*; lithological boundaries without density contrasts are shown by *dotted lines*. (**a**) Tertiary, (**b**)–(**d**) diatomite (increasing density), (**e**) debris flow deposits, (**f**) sand and proximal facies of the diatomites, (**g**) granodiorite debris, (**h**) collapse breccia, (**i**) granodiorite

Comparison of the two study areas

Comparison of the two study areas yields a surprising similarity in their seismic reflection patterns (Fig. 5c) and petrophysical properties (Table 3). Because oil shale was mined at the Messel site down to a depth of about 60 m and because Tertiary sediments of about 30 m thickness cover the maar filling at the Baruth site, the seismic sections have to be shifted vertically about 90 m with respect to one other. The combined section (Fig. 5c) shows the base of the relatively undisturbed sedimentation of organic-rich claystone or diatomite (lithozones D3/D2) coinciding at a depth of about 94 m (tied to ground level at the Messel site). The transition to the intercalation of organic claystone with clastic material (Lithozone D1) is marked by strong reflectors. The bottom of this zone is again indicated at both sites by strong reflections. Below this zone, breccia composed of boulders of granodiorite or amphibolite is indicated by more irregular and low frequency reflections.

Geophysical model

Gravity model

A combined interpretation of the surface geophysical measurements, the results of the borehole logging and the lithological core information confirm the maar-diatreme model for both structures. The Baruth and the Messel maars show strong similarities in the geophysical data sets and their interpretation (Fig. 5 and Table 3). Therefore, we discuss the geophysical model for the Baruth maar in detail as typical of preserved maar-diatreme structures.

The lithological information from the boreholes, the logging data, and the interpretation of the seismic lines were incorporated in a 3-D model based on the gravity data. Figure 5 shows one representative vertical section through the gravity model. The model fits well with the measured Bouguer anomaly; the fit is better than 0.3 mGal. The regional gravity gradient is caused by the Tertiary sediments and the granodiorite basement, whereas the local anomaly can be related to the low densities of the diatomites and debris flow deposits. The model is in accordance with the maar geometry derived from the seismic investigations. The combination of seismic and gravity interpretation indicates diameters of the maar of about 900 m N–S and 1100 m E–W.

The lower boundary of the laminated sediments in the Baruth 1/98 borehole lies at 232 m. In the gravity model (Fig. 8), the three diatomite model units reflect increasing proportions of turbidites and increasing compaction of sediments with greater depth, and therefore, increasing density. The two upper diatomite units (50–186 m) with densities of 1,350 kg/m^3 and 1,500 kg/m^3 (Table 1) are responsible for most of the gravity anomaly. In the seismic section, they appear as a nearly transparent zone, representing sedimentation into a stable lake (lithozone D3/D2). The corresponding stratigraphic unit in the Messel Pit is the black shale. Model unit "diatomite 1" involves diatomite without (or only a low proportion of) turbidites (lithozone D3) and the upper part of lithozone D2 with an increasing proportion (up to 50%) of turbidites. The boundary between "diatomite 1" and "diatomite 2" in the gravity model was chosen with respect to the strong seismic reflector at 140 m depth caused by phonolitic ash layers. These two gravity units represent a two layer model with two distinct densities; a one layer model with a density gradient would be more realistic, but the results from matching the Bouguer anomaly are very similar for both models.

The sedimentation at greater depth is characterized by a high content (50-100%) of turbidites within the diatomite. The mean density increases slightly, but density values vary within a wide range (Table 1; cf. Table 2); this zone (lithozone D1) is modelled by the "diatomite 3" unit. In the Messel structure, this unit corresponds to the uppermost part of the shale-dominated sediments.

At the base of the former maar lake, diatomites or shales are absent and sedimentation is dominated by clastic debris flow deposits (lithozone C). The density of the sediments increases significantly and reaches values of more than 2,000 kg/m^3 (Table 3). A sequence of several strong reflections occurs in the seismic sections from this zone (Fig. 5a).

In order to explain the gravity gradients, we have to assume an asymmetry of the lake sediments. The thickness of the sandy layer and the granodiorite "debris" is greater at the southern rim of the maar than in the north, but the thickness derived from the gravity data depends largely on the difference between the density of sand and granodiorite. The gravity modelling indicates that the dip of the "sand"

Table 3 Mean values or ranges of petrophysical properties of sediments of the stabilised and early lake period (lithozones D, C) and the first sedimentation (lithozones B) measured in the Baruth 1/98 and Messel 2001 boreholes. In particular, the density and velocity are significantly lower in the lithozone D than in the deeper sediments

Lithozone	Bore-hole	Thickness (m)	Density (kg/m)	Velocity (VSP) (m/s)	Gamma ray (API)	Susceptibility (10^{-4} SI)	Resistivity (Ωm)
D	Baruth	196	1,430	1,600	48	5	13
	Messel	>143	1,400	1,600	55	1	16
C	Baruth	17	2,100	2,500	80	10	10
	Messel	85	1,500–2,500	1,800–3,500	50–100	1–800	20
B	Baruth	>23	2,600–3,000	3,500	120	1.5–100	2,000
	Messel	12	2,200	2,000	80–120	1–50	15

unit in the south (45–50°) is not as steep as in the north (50–60°).

The Baruth 1/98 borehole does not penetrate the granodiorite as implied by Fig. 8, but ends in the collapse breccia. The depth of the boundary between the granodiorite and the granodiorite "debris" in the gravity model was chosen with respect to the density values derived from the borehole measurements (Table 1).

Neither the gravity survey nor the seismic survey gives detailed information about the diatreme itself. The density of the breccia is close to that of the surrounding rock, so seismic reflections are missing. Only a few steep and horizontal reflections at a depth of about 500 m in the seismic profile of the Messel Pit give some indirect hints of layered diatreme breccias (Fig. 5b).

Magnetic model

The interpretation of the magnetic anomaly is more difficult and differs at the two locations. The Baruth boreholes do not reach the magnetic body, as verified by susceptibility and magnetic field logs as well as by the physical properties of the cores. Therefore, the source of the anomaly must be at depths greater than 100 and 280 m, respectively. Furthermore, the magnetic source body should not give rise to a gravity signal, because the Bouguer anomaly is totally explained by the lacustrine sediments. Two alternative models can be considered.

The first interpretation is based on the assumption of two magnetic bodies. One body in the upper part of the maar diatreme is interpreted as a remnant of cooled magma. The other body, interpreted as volcanic debris, lies below the Baruth 2/98 borehole. The model anomaly is calculated with magnetization inclination I=67° for both bodies (recent inclination) and intensity M=2.6 A/m and 4.2 A/m summarizing induced and remanent magnetization.

The second model consists of only one magnetic body, extending from the location of Baruth 2/98 to the centre of the gravity anomaly. This body is also interpreted as volcanic debris that slid from the rim to the centre of the crater, and therefore has a greater extent. Its magnetization value is assumed to be I=67° and M=6.6 A/m. Both models can explain the observations of the surface surveys as well as the magnetic field measured in the borehole.

Unlike the Baruth boreholes, the Messel 2001 borehole penetrated a magnetized body, as it can be seen in borehole logs (magnetic total field anomaly, susceptibility) and core logs (susceptibility, remanent magnetization). The lower part of the tuff between 306 and 362 m is inversely magnetized (up to 10 A/m). However, the physical properties of that part of the tuff can only explain 60% of the observed magnetic anomaly at the surface. Consequently, the existence of another magnetic source is postulated at greater depth, not reached by the borehole.

The question, why only the lower part of the tuff layer is strongly magnetized, is the matter of an ongoing investigation funded by the German Science Foundation (DFG). It could be that parts of the tuff is welded and thus magnetized in place, and other parts deposited as air-fall with little alignment of the separate magnetic moments. However, a preliminary examination of the drilled rocks does not show any distinct petrological differences. On the basis of some tests with laboratory-produced thermoremanent magnetization (TRM), we assume that the more strongly magnetized pyroclastic layer has been heated up to 300°C or more—higher than the 100°C postulated by Lorenz (1986). The magnetic susceptibility of samples from the upper part (240–306 m) is comparable to that of the lower layer (306–362 m); microscopic distribution of rounded mineral grains and laboratory-produced TRM values are similar for both levels, but the upper level's intensity of natural remanent magnetization (NRM) is only 5% of that of the lower level.

Conclusion

The combined geophysical investigation of two buried maar structures represents the first comprehensive collection of geophysical data and observations. The same procedure can be used to investigate similar geological situations elsewhere (e.g. Gabriel 2003).

The combination of gravity and ground magnetic surveys has been shown to be an excellent tool for the detection and identification of buried maar structures. Their prominent properties are an almost circular gravity minimum as the result of the crater being filled with limnic sediments of low density, and a similar roughly circular magnetic anomaly as evidence for the volcanic character. The magnetic anomaly is mainly caused by tuff or basalt from the end of the phreatomagmatic event. Both anomalies are regular and located close together even though they do not coincide. The magnetic anomaly seems to be smaller than the gravity anomaly.

The internal structure of the maar-lake sediments can be identified only by seismic data yielding a highly detailed image. Laminites of the late lake period cause a lack of any strong reflections in the seismic sections; this zone is nearly "transparent". The underlying reflectors represent irregularly spaced turbidite layers interbedded with weak reflective laminites. At their base, a series of debris flow deposits and turbidites (sediments of the early lake period) causes strong seismic reflections. The disappearance of strong reflectors marks the base of the former maar crater. The lateral boundary of the maar diatreme is difficult to find in the seismic sections.

Seismic information allows geophysical modelling of the maar taking into account the shape of the gravity anomaly structure. Optimal drilling locations can be selected on the basis of the geophysical prospecting results. Boreholes enable the measurement of a broad range of in-situ parameters. Laboratory measurements on core samples are necessary to determine the remanent magnetization as a physical indication of the maar's genesis.

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