Origin of magnetic anomalies in pyroclastic rocks of the Messel volcano: insights into a maar-diatreme-structure

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Origin of magnetic anomalies in pyroclastic rocks of the Messel volcano: insights into a maar-diatreme-structure

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1. General information

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Topic:
Origin of magnetic anomalies in pyroclastic rocks of the Messel volcano: insights into a maar-diатreme-structure

Report period: 02.03.2004 – 31.03.2007
Ro 2170/4-1 first application
Ro 2170/4-2 continuation application

List of publications

Submitted manuscript


Peer-reviewed articles related to the project:


The papers are attached as appendages.
2. Working and result report

Questions and goals of the project

In 2001 the 433 m deep Messel 2001 borehole was drilled in the centre of the Messel Pit, 25 km south of Frankfurt (Germany). Geoscientific results from this drilling clarified the origin of the circular-shaped basin as a maar-diatreme-structure. The research drilling has given an insight into the diatreme structure below a maar-lake and has provided continues core material and borehole logging of the volcaniclastic section.

In combination with comprehensive geophysical ground survey, the logging and core investigations serve as background information to clarify the origin of ground and borehole magnetic anomalies as observed in such maar structures. Volcaniclastic intra-crater maar-deposits have not been previously investigated by studies on vertical, successive core sections underlying lacustrine crater sediments. Rock magnetic and fragment analytical experiments in combination with the potential field investigations should provide essential data sets for the interpretation of maar-related magnetic field anomalies and contribute to the understanding of the Messel maar genesis.

The data should support a refinement of the computer-based 3D potential field modelling of the diatreme structure.

A reconstruction of the thermal history of the volcaniclastic unit by thermal modelling based on rock magnetic results was also planned.

Development of the work

Based on preliminary work of the project leaders with the engagement of Thomas Nitzsche as Ph.D. student our rock magnetic and image investigations promoted well. The initially intended thermal modelling of the volcaniclastic units was cancelled owing to the advice of the reviewers and as a consequence of deepened geochemical analyses which have been necessary as a result of a negated DFG applicant for volcanology investigations on Messel units as part of the DFG-Bündel concerning Messel. Following the recommendation of the DFG a 3D potential field modelling using rock magnetic and gravity parameters in conjunction with other geoscience information was performed to provide constraints on the subsurface structure.

Rock magnetic investigations

Based on the downhole magnetic data, a subdivision of the volcaniclastic section (Fig. 1a) has been made as shown in the Figure 1b. While the MS log with varying intensities tend to increase with depths from the top to the bottom, it is remarkable that the downhole magnetic ΔF-anomalies are mostly pronounced within the lower half of the lapilli tuffs. The lapilli tuffs, as main interest of maar-related magnetic field anomalies show little differentiation on a macro- and microscopic scale and appear as a structureless and unsorted volcaniclastic body with dominating juvenile lapilli and accidental clasts mostly in the range of (sub-)millimetres to centimetres in diameter. The apparent disagreement between logs and the lithological characterisation in macro- and microscopic scale has been solved first by rock magnetic measurements.

Sample preparation and rock magnetic measurements have been performed in the Laboratory of Rock Magnetism in Grubenhagen (GGA Institute, Leibniz Institute for Applied Geosciences), unless otherwise noted. Magnetic susceptibilities have been measured with a Bartington apparatus MS2. Because of polishing problems of the volcaniclastic samples during thin section preparation for microprobe analyses and the predominance of very small-sized Fe-oxides (<5 µm), the identification of the main ferrimagnetic mineral phase turned out to be very difficult. To handle these problem temperature-dependent MS experiments on pulverised samples (using a KLY2/CS2 kappa-bridge, AGICO, in an argon atmosphere) were performed in the Magnetic Laboratory of the Geology Department at the University of Heidelberg. Magnetisation measurements have been realised with a
2G-cryogen magnetometer or with a mini-spin magnetometer for samples with very high NRM intensities. Isothermal remanent magnetisation (IRM), alternating field (AF) and thermal (TH) demagnetisation as well as thermal remanent magnetisation (TRM) experiments have been carried out with instruments from Magnon GmbH (PM I, MI AFD 200 and MI TD 700). Hysteresis experiments at 5 K and 300 K have been measured on small mm-sized samples with MPMS-XL7 (Magnetic Properties measurement System XL-7) at the Department of Geosciences at the University of Bremen and with a variable field translation balance (VFTB), equipment of the Palaeomagnetic Laboratory at Niederlippach (LMU, Munich).

![Image](image1.png)

**Fig. 1a)** Reconstruction of the Messel maar-diature volcano (modified after Lorenz, 2000; Harms et al., 2003) and its schematized lithozones (Harms et al., 2003) in depths of 0-433 m. **b)** Downhole magnetic data (Wonik and Salge, 2002) with magnetic susceptibilities MS (left) and deviations of the total magnetic field intensities ΔF (right), performed during the drilling project in 2001.

Measurements of the anisotropy of magnetic susceptibility (AMS) were performed with a KLY-4S kappa-bridge (AGICO) in the Structural Laboratory at the Institute for Geology of the University of Würzburg. Thin sections were produced at the Institute for Mineralogy of the University of Würzburg for microprobe analyses (CAMECA SX51), whereas magnetic minerals have been analysed at the Mineralogical Institute of the University of Heidelberg.

**Image analyses**

To elucidate and assist to the rockmagnetic properties image-analytical data of juvenile fragments have been collected with the aim to get information of differentiation of size, fraction volume (area) and flattening ratio (deformation) of the particles. The quantitative image analytical investigations of size and abundance of lithics have been performed with the software DIAna V3 (digital image analysis, version 3) which is trademark of Johannes Duyster, BASys (Bildanalyseysteme) Karlsruhe, Germany. One-meter half-cores and thin sections of 1-inch-plugs
have been digitalised and measured with the particles manual modus because of small colour differences and poor, automatic particles identification. The accidental clasts fractions of 27 images (>250 single measurements) have been measured and illustrated in percent; size (mean long axis and mean area), fraction volume (area sum) and shape (flattening ratio) reflect quantities of nine image samples compared with their rockmagnetic parameters (MS, NRM).

Core measurements with a particle size resolution of >2-3 mm have been implemented within an area frame of 100 cm² (200-700 single measurements). For calculation of flattening ratios, only juvenile particles >5 mm have been considered. Achieving a more detailed resolution and measuring of all particles, area sums, mean areas and mean long axes of lithics (with sizes >0.6 mm² or >1 mm) have been calculated on thin section images within an area frame of 600 mm² (130-250 single measurement). For comparison and quality control data of the relatively small area frames of the thin sections, area sums of the lithics have been also measured on 20 core images. It is consequent that the 2D cross sections do not really reflect the true size values. However, magnetic fabric studies proved the weak anisotropy texture of the volcaniclastic rock samples. Therefore, it is inferred that the ratios bear only small mistakes by using 2D instead of 3D values. The volumetric proportion of clasts in a rock is equal to the area proportion of the clasts in any section.

Geochemical analyses

Additional geochemical investigations on juvenile lapilli deposited in vertical successions allow identifying different magma compositions and thus commenting on eruption phases and some depositional aspects during formation of the lapilli tuffs. The geochemical composition of the magmatic phase can be studied by the juvenile fraction. Because of large amounts of small-sized particles in these rocks, it is difficult to acquire whole-rock chemistry of the juvenile material. Avoiding the time-consuming selection of single juvenile particles to produce sufficient rock powder for preparing XRF-tablets and to be ascertained that the geochemical results are limited to one juvenile particle, averaged microprobe scan analyses of single particles have been used for the evaluation of major element distribution.

Major elements of juvenile fragments have been analysed with CAMECA SX50 electron microprobe (Institute for Mineralogy, University of Würzburg), using international rock standards for calibration and data quality control. Matrix correction has been carried out by using the CAMECA PAP-program. At least 3 particles per sample have been investigated, reflecting approximately 200-500 single measurements per sample. Trace elements were analysed by inductively coupled plasma mass spectrometry (ICP-MS) at the Institute for Mineralogy (University of Würzburg), using calibration of NIST 612 50 ppm glass and values from Pearce et al. (1997). Data evaluation was carried out with the program GLITTER version 3.0.

Potential field modelling

Ground survey data from the GGA Institute and the University of Mainz have been used for the 3D potential field modelling. The ambiguity of potential field interpretation should be reduced by considering results of several geoscientific methods: lithological results of several Messel boreholes, seismic information, density parameters from the 2001 research well and results of the core and/or plug magnetic measurements. Additionally an appropriate elevation model, representing the topography of the Messel area in grid format, was inevitable. The interactive, graphical computer system IGMAS (Interactive Gravity and Magnetic Application System) for interpretation of potential fields (gravity and magnetics) by means of numerical simulation was used. The modelling procedure is based on “trial and error” methods. The algorithm used for potential field calculation is based on triangulated polyhedrons (Götze, 1978). The aim of the 3D modelling was to combine the gravity and magnetic field planes to fashion a single maar-diatrem-structure.
Presentation of results and discussion

Rock magnetic investigations

Using the methods of magneto-mineralogy, the acquisition of IRM and hysteresis experiments, the ferrites within the juvenile lapilli point to very similar compositions (Curie temperatures and geochemical analyses), coercivities and grain sizes. The (titanio)-magnetites with a near magnetite composition are intermediate in grain size between magnetically stable SD and instable MD particles. Stability or dispersion of negative inclinations signalises the strength of magnetisation highest within the lower half of the lapilli tuff. NRM intensities trace the ΔF-curve and are also highest within the lower half of the lapilli tuff. The dominant negative inclinations correspond to the reverse polarity in the Eocene Chron C21r (c. 48 Ma).

Despite the similarities in ferrimagnetic properties of the volcaniclastic material, the magnetic signature illustrated by log-comparison of NRM and MS measurements reveals a remanence partitioning. The onset of the clearly reverse magnetisation is realised below 307 m depth and generally greatest within the lower half of the lapilli tuff up to the appearance of the underlying diatreme-breccia. This can also be demonstrated by a log of NRM measurements and their magnetic inclinations (Fig. 2). NRM values trace the anomalies of the ΔF-curve in a range from 0-15 A/m. The lower half of the lapilli tuffs depicts stable negative inclinations between -30° and -56°, whereas in units I and V (Fig. 1) and in the diatreme-breccia inclinations are more dispersed between -77° and +39°. In coincidence with the Eocene age of Messel calculated after Mertz and Renne (2005), the reverse magnetisation of the volcaniclastic deposits suggests a remanence acquisition earliest during the ocean anomaly C21r (47,907-49,036 Ma) (Fig. 2; Rolf et al. 2005).

The Messel averaged inclinations of I = -40° are too gentle when compared with volcanic Tertiary rocks of Southwest Germany, possessing palaeo-inclinations of I = 61.5° (Nairn and Negendank, 1967). The magnetic inclination flattening most likely resulted from compaction and subsidental processes (Lorenz, 2003), occurred after deposition of the intra-crater volcaniclastics. Differences in the magnetization of the material have been demonstrated in demagnetisation experiments. AF demagnetisation measurements of samples inside the anomalies (AF) appear to be more stable than material deposited outside. Thermal demagnetisation experiments (Fig. 3 left) also indicate that magnetic remanence instability is greatest within the upper part of the lapilli tuffs.
The differently acquired or “locked” magnetisations of the volcaniclastic material can be interpreted by differently availed depositional temperatures. In this context, heating experiments may explain the origin of the magnetic partitioning. Although the whole volcaniclastic material had the possibility to acquire similar remanent magnetisations (due to similarities in ferrimagnetic properties), only the lower half of the lapilli tuff shows high remanence magnitudes. This is because depositional temperature at unit II-IV has been higher than at units I, V and in the diatreme breccia. Thus the temperature effect was most pronounced between 307 m and 373 m, where the erupted lapilli tuff acquired its strongest TRM. Heating experiments compared to the initially acquired NRM (Fig. 3 right) favour depositional temperatures <300 °C for the material outside the anomalies, whereas material inside the anomalies most likely was deposited at temperatures >300 °C. Slightly different absolute values of acquired TRM at 600 °C (15.2 A/m and 22.3 A/m) can be explained by the occurrence of different susceptibilities. Increasing magnetic susceptibilities with depth (240-360 m) point to an increasing volume portion of juvenile components. Considering the heat source within the volcaniclastic units, the abundance of different sized juvenile lapilli and their frequency of occurrence give reason to study the juvenile fragments in more detail.

Fig. 3 Thermal magnetic experiments illustrated on seven exemplary samples deposited out- and inside the ΔF-anomalies. a) Thermal demagnetisation experiments of the sample from 267 m (outside ΔF-anomalies) the reveal a broad range of blocking temperatures and a relative weak remanence behaviour, due to a quick loss of magnetisation during stepwise heating. The Blocking temperature spectra of the sample from 351 m depth (inside ΔF-anomalies) are relatively narrow, reflecting a strong acquired remanence. c) TRM experiments inside and outside the anomalies result in very similar stepwise acquisition of their magnetisation and blocking temperature spectra. The samples differ in their initial NRM and show small differences in their absolute TRM at 600 °C.
The erupted rocks appear as unsorted and structurally pyroclastics. Nevertheless, AMS measurements reveal magnetic fabrics in these rocks. According to the rock magnetic properties and high bulk MS intensities ferrimagnetic components are dominant throughout the lapilli tuffs. Even though the AMS data of the Messel volcaniclastics are cryptic and the interpretation speculative it is supposable that a compaction-resulted, vertical stress field interacts with a tectonically horizontal stress field of the Rhine graben tectonics.

Image analyses

The Messel maar lapilli tuffs (240-373 m) predominantly consist of clast-supported fragments, with a minor ash matrix fraction. The clasts or lithics are classified as either juvenile or accidental (Fig. 4). The juvenile lapilli are unsorted and vary in grain size. They are mostly in the range of 0.2-1 cm, rarely exceeding 2 cm in diameter. Accidental clasts are mostly angular, but may show small, rounded components, too. Their grain sizes are mostly in the same range as the juvenile fragments and very rarely show blocks of several decimetres in diameter. The combination of image analytical investigations on cores and thin sections reveal small-scaled information of the Messel volcaniclastic particles which could not be observed by lithological descriptions after Felder et al. (2004).

Comparing susceptibilities with the accidental clast fraction, no dependency is evident. A negative correlation of the parameters would suggest “MS dilution” due to high abundances of accidental clasts. The MS increase with depth would imply a decrease of the accidental clast fraction. The quantitative image analyses rule out this hypothesis. Generally, the volcaniclastic rocks are difficult to differentiate and can be regarded as virtually homogeneous. Comparing the particle grain sizes with the MS behaviour of the samples, it is obvious that the juvenile fragments follow the downhole, linear MS trend with increasing values.

Our small-scale image analytical investigations on juvenile fragments prove to be valuable for understanding the rock magnetic character (MS trend and NRM signature) of the tuffs and show distinct differences in their particle grain size, degree of relative fraction dominance and shape. Juvenile fragments of the strongly magnetised part of the volcanic body are generally larger, more frequent and have higher flattening ratios than in the slightly magnetised body.

Geochemical analyses

The clear subdivision of the tuffs is also accomplished by our major element analyses of the juvenile fraction. Particles deposited inside the strongly magnetised part (II) of the volcanic body have higher SiO$_2$, Al$_2$O$_3$ and K$_2$O, but lower MgO and CaO concentrations than samples deposited outside

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<tr>
<th>section I</th>
<th>core samples</th>
<th>thin sections</th>
<th>description</th>
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<tr>
<td>50 cm</td>
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<td>- mostly clast-supported, structureless, poorly sorted and juvenile-rich lapilli tuffs</td>
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<tr>
<td>303 m</td>
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<td>- sub-rounded, juvenile fragments with low vesicularity (&lt;5%) and low richness of phenocrysts (&lt;5-10%)</td>
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<tr>
<td>2 cm</td>
<td></td>
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<td>- angular to rounded accidental clasts</td>
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<td>- frequently altered ash matrix</td>
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<th>section II</th>
<th>core samples</th>
<th>thin sections</th>
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<td>500 m</td>
<td></td>
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<td>- as above, but with higher concentrations and larger grain sizes of juvenile fragments</td>
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Fig. 4 Photographs of two core and thin section samples at the magnetic boundary zone outside (303 m) and inside (308 m) the AF-anomalies. Lithics are defined as juvenile fragments (j) and accidental clasts (acc.). The ash matrix (m) represents the indefinable portion of very small particles.
(I, III). The chemical analyses of juvenile fragments from the diatreme-breccia (III) possibly correspond to a separate group (Fig. 5).

Interpretation of analytical measurements

In context with rock magnetic studies, image analytical results suggest that the juvenile fragments deposited at higher temperatures (section II) favoured a more effective delay in cooling process (heat loss) of the material than the volcaniclastic rocks deposited at lower temperatures (section I and III). During eruption and subsequent deposition of the material within the Messel diatreme-structure, the temperatures of the tuffs in section II have been high enough (above Curie temperatures of near magnetite-composition) to acquire TRM.

Due to petrographical investigations of the juvenile particles, the degree of crystallinity and volatile content does not change much, so that temperature and chemical composition most likely control their different rheological behaviour. Ignoring the geochemical character, high temperatures of the juvenile fragments very likely caused their higher degree of deformation. This statement agrees with the occurrence of agglutinated formations of some particles at roughly 350 m, showing here their highest degree of flattening ratios and very high NRM intensities, too. It is possible that the water/magma mass ratio, which can be one crucial parameter for the degree of fragmentation of the material, has varied (Fischer and Schmincke, 1984; Lorenz, 1986; Wohletz, 1986; Vespermann and Schmincke, 2000). Larger particles in section II possibly result from lower mixing ratios. Concerning the Messel explosivity (the efficient conversion of thermal energy into kinetic energy), the particles in section II indicate a rather strombolian eruption style with lower water/magma mass ratios; the particles deposited in section I (and section III) favour a more hydrovolcanic eruption style with higher water/magma mass ratios, typical for most maar-related deposits.

The geochemical variation in all sections points to at least two different eruption phases. The geochemical division can not be clearly reproduced by trace element analyses of the juvenile fragments. However, REE data with very high LREE concentrations show a well-defined association to potassic continental riftzone-magmatism of typical within-plate basalts.

![Fig. 5 Total alkalis (Na₂O+K₂O wt.% versus silica diagram with groupings of the juvenile material from inside (II) and outside (I, III) the strongly magnetised body (after Middlemost, 1980).](image)

The data suggest a clear sub-division of the lapilli tuffs into a two-condition eruption phase at the end of the Messel volcanic activity. Image analytical and major element data support the rockmagnetic results of the lapilli tuffs and separate the volcaniclastic material into a relatively hot, undifferentiated eruption phase and a colder, differentiated phase. Size, shape and amount of the juvenile particles account for the temperature evolution and heat conditions during/after deposition of the Messel lapilli tuffs.
Potential field modelling

The combined interpretation of the surface potential field measurements, interpretation of the seismic lines, the results of the borehole logging and the lithological core information confirm a maar-diatreme-structure model. The gravity model fit well with the measured anomalies; the magnetic model is more simplified but well-approximated. While the gravity model mainly attributes to the density parameters selected for the lacustrine sediments (upper part of the maar-structure), the magnetic model is based on magnetisation intensities of the volcaniclastic material (lower part of the maar-structure). Figure 6a shows one representative vertical section through the gravity and magnetic models, and confirms their well-defined accordance between measured and modelled potential fields. The lapilli tuffs display here their greatest thickness. According to current research studies on the volcaniclastic rocks, the western half of the maar-structure is assumed to be the preferred depositional area (pers. communication, Felder, 2006). Thereby, it does not necessarily implicate that the magnetised material is dominant in the volcaniclastic facies. The volcaniclastic source investigations are based on country rock studies which are supposed to clarify possible vent movements and involvement of the rocks surrounding the diatreme-structure. The so-called “flying carpet” illustration shows the modelled 3D “snapshot” of the Messel subsurface (Fig. 6b).

Finally, it has to be mentioned that the magnetic model includes the calculated magnetisations deduced by one single borehole information. As described in the rock magnetic chapter the NRM s are produced by different emplacement temperatures. The same thermal history and acquisition of the TRMs are not ascertained in the Messel lateral volcaniclastic successions. Consequently, the correctness of the modelled geometry of the volcanic edifice is questioned. The complexity of these deposits with their appropriate magnetisations can only be clarified by additional information of cored boreholes, drilled in direction to the Messel maar-margins. The Messel potential field 3D model explains the magnetic anomaly on the surface.

Fig. 6a) Modelled gravity (blue line) and magnetic (red line) potential fields. The vertical section crossing the Messel area shows the well-defined model and the slightly asymmetrical maar-structure (compare legend in Fig. 32). b) 3D illustration of the Messel subsurface with lacustrine sediments (light green and yellow) and lapilli tuffs (purple).
Conclusions and perspectives

Rock magnetic investigations on the Messel volcaniclastics have shown that they are very instrumental in identifying primary deposits. The used rock magnetic methods in combination with small-scale image analytical and geochemical methods explain the downhole and ground magnetic anomalies of Messel. The interdisciplinary studies also provide insights into emplacement conditions of the intra-crater pyroclastics. The remarkable magnetic signature could be clarified by thermal magnetic experiments. Pyroclastic fragment investigations argue for different heat and magma source conditions. The last eruption phases of the Messel volcanic activity and its post-eruptive events can be described and illustrated (Fig. 7) as follows: Magma ascended along a conduit within the pipe. The melt penetrated through layered deposits of the diatreme-breccia or older eruption phases and encountered groundwater in depths of several tens of meters (up to hundred meters) below the pre-existing and partly subsided maar-craters. The magma/water interaction resulted in a (phreato-) magmatic eruption (eruptive phase one). It is very likely that the eruption column was relatively low and the intra-crater depositional process rapid, so that the material was still relatively hot to acquire high remanence intensities (TRM) and stable (negative) NRM inclinations. The particle investigations argue here for the most pronounced temperature effect (maintenance of heat in juvenile particles), a relatively low W/M (water/magma) mass ratio and low fragmentation index. The absence of layer boundaries, especially between the magnetised and non-magnetised lapilli tuff sequences, implicates a fast, subsequent impulse of eruptive phase two. In this stage, the erupted material has been deposited at lower temperatures and is characterised by a slightly smaller amount of juvenile fragments. All criteria infer a high amount of water involved in the eruptive system relative to the first eruptive phase, which resulted in a more energetic event (higher degree of magma fragmentation) and thus in a possibly higher eruption column. Thereby, relatively rapid and effective heat loss of the juvenile particles is given by their slightly smaller grain sizes which correlate with their thermal diffusion time (Gudmundsson, 2003). Possibly, the longer ballistic aerial duration time and the geochemically more differentiated character of the juvenile fraction (evolved magma) are favours for the colder eruptive phase 2. Thus, the intra-crater deposits acquired weak remanent magnetisations. The primary origin of deposition is not questioned because of the lack of totally disordered palaeomagnetic data and dominant negative inclinations in most parts of the deposited material.

Similar trace element ratios of the magma involved in both eruption stages indicate a magmatic source from the same magma chamber. However, the major element pattern of the juvenile fragments favours magmas from different magma chamber levels.

The clear major element differentiation from the first eruptive phase provides the potential of a newly evolved magma conduit (eruptive phase 2b). Vent migration is a possible and observed phenomenon in maar-related volcanoes (Sohn and Park, 2005), but speculative and incomprehensible with the rapid and successive Messel eruption stages. Post-eruptive phases signal the final stages of the Messel maar formation. They are dominated by erosive processes of the crater walls, compaction of the material and subsidence processes (Lorenz et al., 2003; Lorenz and Kurszlaukis, 2007). Due to the relatively high groundwater level and lacking surface drainage, the Messel maar crater was filled with a lake. Lake beds and other maar-related deposits accumulated and were affected by further subsidence and slumping processes as long as compaction of the underlying diatreme fill continued.

For the first time, thermal magnetic temperature studies on pyroclastic successions within a diatreme-structure could clarify the existence of downhole magnetic anomalies by different emplacement temperatures. Although it was thought that maar-related deposits of phreatomagmatic origin deal with relatively low eruption temperatures, the lower half of the
Messel pyroclastics argue the converse. Generally, when dealing with magnetic anomalies which are implicative for a subsurface diatreme-structure, it has to be considered the existence of pyroclastic rock units, which are affected by high emplacement temperatures, and their acquisition of high thermal remanent magnetisations. These TRMs can produce magnetic anomalies, detectable by ground survey and borehole measurements. The Messel drilling project 2001 with full core recovery provides a wide variety for on-going research interests. The comparison of the volcanioclastic material with volcanic rocks of the neighbouring volcanoes (e.g. Prinz of Hessen, Großzimmern) or dyke intrusions will enhance chances for the volcanological interpretation of the entire “Sprendlinger Horst volcanic field” existence. With respect to the pyroclastic edifice of the maar-volcano, detailed investigations on accidental clasts and their geological origin related to the geological environment will improve knowledge about the eruptive processes occurred at the end of Messel activity.

Drillholes give just a vertical insight into the complex structure of a maar-diatreme. A combination of the detailed information from boreholes with field observation from exposed diatreme structures (e.g. as realized in the Little Hungarian Plain) will further contribute to the understanding of these volcanic systems. In this context a preliminary study (2 diplom theses, University of Würzburg) of the Sag Hegy volcano in Hungary has been done in 2007.

Fig. 7 Schematic cross sections through the upper level of the Messel maar-diatreme-volcano in syn- and post-eruptive stages, showing the deposition of the magnetised and non-magnetised lapilli tuff sequences as well as the evolution of the Messel basin up to the maar-lake stadium.
**Working team and cooperations**

**Working team:**
- C. Rolf (Leibniz Institute for Applied Geophysics (GGA-Institut) Hannover) project leader
- H. de Wall (University of Würzburg), co-leader.
- T. Nitzsche, (Leibniz Institute for Applied Geophysics (GGA-Institut) Hannover) and (University of Würzburg), Ph.D. student
- G. Gabriel (Leibniz Institute for Applied Geophysics (GGA-Institut) Hannover) for support and supervision in potential field modelling
- R. Schulz, H. Buness, T. Wonik and H. Wiederhold (Leibniz Institute for Applied Geophysics (GGA-Institut) Hannover) members of the Messel working group

**Student assistants (funded by DFG):**
- Nina Dworazik, Daniela Renk, Verena Streit and Fabian Richard

**Cooperation with:**
- V. Bachtadse and R. Leonhard (LM-University of Munich) for discussion and support on variable field translation balance (VFTB) measurements.
- V. Lorenz and B. Zimanowski (University of Würzburg) for discussion on volcanology, magmatism and physics of volcanology.
- A. Kontny (University of Heidelberg) for magnetic susceptibility experiments on pulverised samples
- U. Blei and T. Frederichs (University of Bremen) for hysteresis experiments at 5 K and 300 K.
- U. Schüßler und R. Klemd (University of Würzburg) For trace element analyses by inductively coupled plasma mass spectrometry (ICP-MS) and microprobe analyses of the juvenile fragments

**Presentations of results on workshops and conferences:**


**Qualification of scientific junior staff**
In the frame of this project one Doctoral thesis (Thomas Nitzsche) has been done. An electronic version of the thesis is included (Appendix VI: CD). T. Nitzsche was honoured at the Second International Maar Conference at Lajosmizse / Kecskemet, Ungarn for his talk: “Origin of magnetic anomalies in volcaniclastic units of the Messel Maar-Diatreme (Germany)”. After finishing his studies he got a permanent position at Heraeus Holding GmbH, Hanau.
3. Summary

In 2001 the 433 m deep Messel 2001 borehole was drilled in the centre of the Messel Pit, 25 km south of Frankfurt (Germany). Geoscientific results from this drilling clarified the origin of the circular-shaped basin as a maar-diatreme-structure. Recovered deposits consist of lacustrine sediments (0-240 m) and volcaniclastic rocks such as lapilli tuffs (240-373 m) as well as rocks of the underlying diatreme breccia (373-433 m). The lapilli tuffs, as main interest here, show little differentiation on a macro- and microscopic scale and appear as a massive and unsorted volcaniclastic body with dominating juvenile lapilli and accidental clasts mostly in the range of (sub)millimetres to centimetres in diameter.

Rock magnetic properties measured on core samples of the volcaniclastic units can explains the origin of downhole magnetic anomalies detected during the drilling project in 2001. Magnetic behaviour of the erupted material is related to fine-grained, Fe-rich (titano-) magnetite, which are dispersed within the juvenile lapilli. Temperature-dependent susceptibility experiments, isothermal remanent magnetisation and hysteresis investigations demonstrate similar ferrimagnetic properties throughout the volcaniclastic material, in terms of composition, coercivity and grain size (pseudo-single-domain particles) of the ferrimagnetic minerals. Thus, during emplacement of the erupted material, the ferrimagnetic minerals had the same remanence acquisition potential.

However, demagnetisation experiments show different magnetic stability behaviour of the acquired natural remanent magnetisation (NRM). Heating experiments prove the acquisition of thermal remanent magnetisation (TRM) dominated by temperature effects which could have been occurred during eruption and deposition of volcanic material, forming the Messel maar-diatreme. It is assumed that the upper half of the lapilli tuffs was deposited at relatively low depositional temperatures (<300 °C), whereas the material of the lower half took advantage of higher temperatures (>>300 °C). To understand the rock magnetic character within the Messel maar-diatreme-facies, particle grain sizes, the degree of the relative fraction dominance and the shape of the juvenile fragments have been studied in more detail. Image analytical methods as well as major and trace element analyses on the juvenile fraction support the clear subdivision of the lapilli tuffs. These findings in combination with rockmagnetic data indicate a separation into a relatively hot, geochemically undifferentiated eruption phase and a colder, differentiated phase. A two-condition eruption stage at the end of the Messel volcanic activity is suggested. The juvenile particles account for the temperature evolution and heat conditions during deposition of the Messel tuffs and contribute to the origin of magnetic field anomalies.

Based on gravity parameters and the results of magnetisation properties, the potential field 3D-model of the Messel subsurface explains the negative ground anomalies, calculates the mass and volume parameters of the drilled lithozones and shows the asymmetric appearance of the diatreme-structure.