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## 3D MT Characterization of Two Geothermal Fields in Iceland

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### ABSTRACT

Three-dimensional (3D) magnetotelluric (MT) inversions leading to the characterization of the electrical structure of geothermal reservoirs in a single self-consistent manner and presumably optimal accuracy and resolution are now feasible. Our work focused on two large geothermal fields – the Hengill and Krafla volcanic complexes, 200 km apart, and both known as high-temperature systems located within neo-volcanic zones of Iceland. This is the first full 3D MT inversion of Krafla MT dataset. The inverted model of electrical resistivity reveals the presence of highly resistive near surface layer, identified as unaltered porous basalt, which covers a low resistivity cap corresponding to the smectite-zeolite zone. Below this cap a more resistive zone is identified as the epidote-chlorite zone or also called the resistive core. Resistivity in the upper 1-2 km does not to correlate with lithology but with alteration mineralogy. At the site of the IDDP well, which encountered magma at 2.1 km depth, the resistivity image shows high resistivity most likely due to epidote-chlorite geology. Just to the northwest of the well, however, an intrusive electrically conductive feature has been imaged rising from depth, and has been interpreted as a magma reservoir. A possible explanation for the magma encounter at the IDDP well is the existence of pathways or fissures connecting the magma chamber to the well. The MT response to magma pathways is not to be discernible in the data. Hengill geothermal area can be divided into two major complexes, one in the southwest and one in the northeast. The inverted model identified two low-resistivity layers. The nature of the uppermost low-resistivity layer and the increasing resistivity below is due to hydrothermal mineral alteration while the nature of the deep low-resistivity layer is not yet well understood. 3D MT inversions of Krafla and Hengill data sets showed that this approach is very promising in imaging geothermal reservoirs and that knowledge of the subsurface electrical resistivity can contribute to a better understanding of complex geothermal systems.

### Introduction

A critical component in understanding the properties of complex geothermal reservoirs, typical of the Iceland geothermal fields, is a technology providing images of subsurface structures, which control geothermal fluid flow. Electrical resistivity is a primary physical property of the Earth strongly influenced by hydrothermal processes present in geothermal reservoirs. If mapped, resistivity can be used to infer untapped fracture systems and regions of increased permeability and fluid content, as well as conductive alteration of minerals (clays, etc.) due to natural or induced fracturing arising from hydraulic stimulation of the reservoir. Magnetotellurics (MT) has a long history in geothermal exploration. 3D MT modeling and inversion has emerged as a promising technique to model and image geothermal reservoirs in a single self-consistent manner at presumably optimal accuracy and resolution. This will be demonstrated on MT data acquired over the Krafla and Hengill geothermal fields (Figures 1 and 6) in Iceland.

### MT Data Analysis and Inversion

MT exploits naturally occurring, broadband electromagnetic (EM) wave fields over the Earth's surface as sources to image underground resistivity structure. The EM fields arise from regional and worldwide thunderstorm activity and from interaction of the solar wind with the Earth's magnetosphere. These EM sources are remote and have a high index of refraction of the Earth relative to the air, therefore the EM waves are assumed to be planar and to propagate vertically into the Earth. The waves are arbitrarily polarized over a 3D Earth, which requires a tensor formulation, in other words a vector measurement of the EM fields, to completely represent the subsurface geoelectric structure.

The horizontal EM field spectra ( $E_x$ ,  $E_y$ ,  $H_x$ ,  $H_y$ ) are inter-related by

$$E = [Z] H$$

where  $Z$  is a 2x2 tensor, obtained for each MT recording station as a function of frequency. Apparent resistivity and impedance phase quantities, that are more intuitive to inspect and interpret (Vozoff,

1991), can be readily obtained by manipulating the elements of the impedance tensor off-diagonal components.

For both geothermal fields, MT data were recorded for frequencies between 0.003 and 300 Hz. For inversions we used three points per decade, total of 15 frequencies. MT soundings were corrected for static shifts using TEM data prior to the inversion. Full impedance matrix was inverted, and apparent resistivity and phase calculated for xy and yx-modes. An initial model for both 3D inversions was a five-layer model with a resistive surface layer, a shallow low-resistivity layer, an intermediate high-resistivity, a deep low-resistivity layer and a relatively resistive basement.

Our ultimate aim was to construct 3D resistivity models of the geothermal systems in studied areas and use them to better understand their structure. To accomplish this goal we applied an inversion process, where the observed impedance data were fit in a

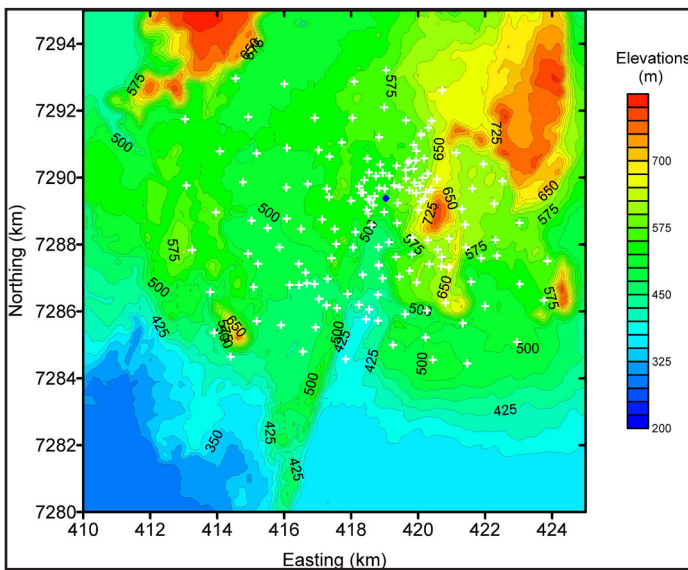


Figure 1. Krafla MT site and elevation map.

least squares sense to model data. The model data were produced by solving Maxwell’s equations for 3D resistivity variations and plane wave source excitation at a discrete set of frequencies. These frequencies correspond to those used to specify the impedance tensor in the field measurements. To stabilize the inversion process, additional constraints were added such as spatial smoothing of the resistivity model. The 3D MT inversion code (Newman and Alumbaugh, 2000; Newman et al., 2003) was run on 5145 cores of NERSC Cray XT4 Franklin system. Total processing time was on the order of 200 hours.

### Krafla Geothermal Area

The Krafla volcanic system is located within the neo-volcanic zone in northeastern Iceland and consists of a central volcano with NNE-SSW trending fissure swarm and

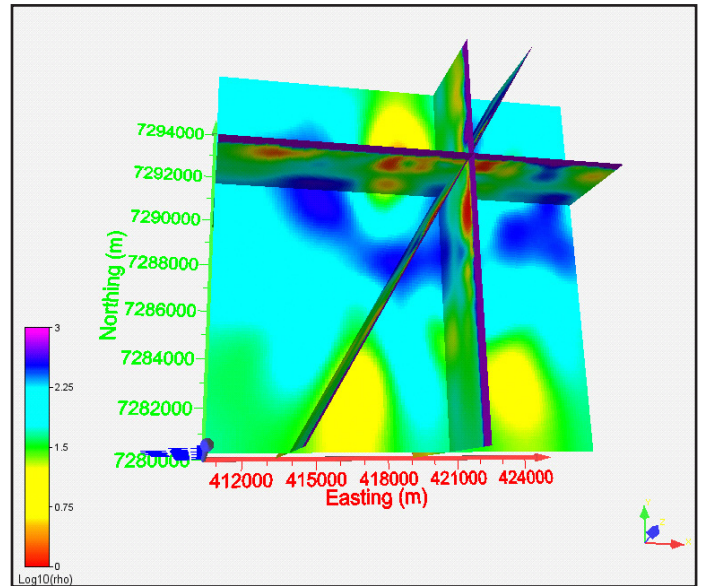


Figure 2. 3D resistivity model of the Krafla geothermal area.

ESE-WNW transform graben running through it. Figure 1 shows elevations in 15x15 km study area of the Krafla volcanic system along with 102 MT soundings (white symbols) that were used in the 3D inversion. The blue diamond indicates the location of the IDDP (Iceland Deep Drilling Programme) well. MT data were acquired during 2004–2006 campaigns by several research groups.

Figure 2 shows a cut-away view of the 3D resistivity model recovered by the inversion, and Figure 3 shows an example of the data fits for both modes of resistivity (on the left) and phase (on the right). Predicted (red curves) Zxy and Zyx, apparent resistivity and phase data from the model show good correspondence to the field data (black symbols). The data error misfit went from 432 to 1.68 for the final iteration.

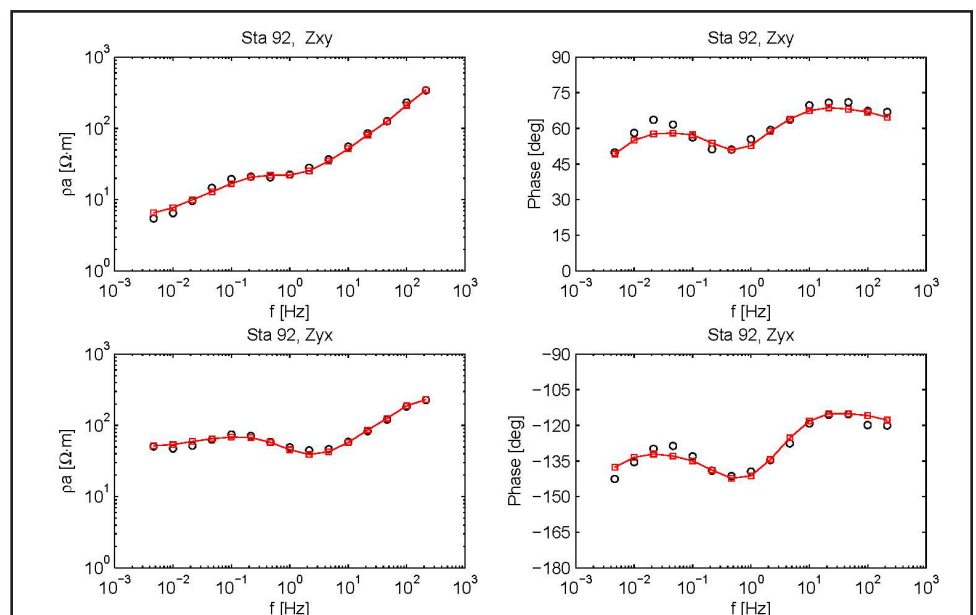


Figure 3. Example of data fits for the 3D resistivity model shown in Figure 2. Calculated (predicted) data are shown as red curves, while the field data are shown with black symbols.

This is the first full 3D MT inversion of Krafla MT dataset. The inverted model of electrical resistivity reveals the presence of highly resistive near surface layer, identified as unaltered porous basalt, which covers a low resistivity cap corresponding to the smectite-zeolite zone. Below this cap a more resistive zone is identified as the epidote-chlorite zone or also called the resistive core (Arnason et al., 2010). In the upper 1-2 km resistivity does not correlate with lithology but with alteration mineralogy (Oskooi et al., 2005). The deep low-resistivity zone, which depth varies, appears to be connected to shallow structure through vertical structures, “chimneys”. The deep IDDP well at Krafla encountered magma at the depth of 2.1 km and drilling was stopped. The well is located on the flank of the altered epidote-chlorite resistive zone with low-resistivity structures on both sides, all running in the NNE-SSW direction, which is consistent with the fissure swarm direction. These low-resistivity structures are located in the same areas as Einarsson (1978) magma chambers causing S-wave shadows. The cross-sections in Figure 2 intercept at the well location and the diagonal profile runs in the fissure swarm direction. This illustrates that MT measurements are sensitive to large geological structures, but not to individual fractures filled with magma or other fluids. The low-resistivity structure in the northwest quadrant is interpreted as a magma intrusion that goes down to ~5 km depth. Mortensen et al. (2010) suggest that together with shallow magma chamber basaltic intrusions below 1-1.5 km release enough heat to cause partial melting of hydrated basaltic

rocks at shallow depths but also to cause superheated conditions within the reservoir.

Figures 4a and 4b are resistivity cross-sections at the IDDP well (black vertical line) as a function of Easting and Northing while Figure 5 shows the resistivity model 2 km to the west of the IDDP well along the profile from south to north. At the site of the IDDP well, which encountered magma at 2.1 km depth, the resistivity image shows high resistivity most likely due to epidote-chlorite geology. However, Figure 5 shows that just to the northwest of the well, an intrusive electrically conductive feature has been imaged rising from depth, and has been interpreted as a magma reservoir. A possible explanation for the magma encounter at the IDDP well is the existence of pathways or fissures connecting the magma chamber to the well.

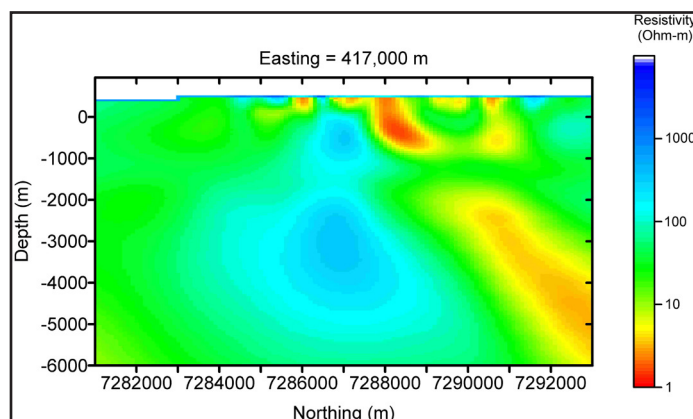


Figure 5. Resistivity cross-section at Easting = 417,000 m taken from the 3D resistivity model in Figure 2.

## Hengill Geothermal Area

The Hengill volcanic complex is located in the southern end of the western volcanic zone of Iceland. It is considered to be

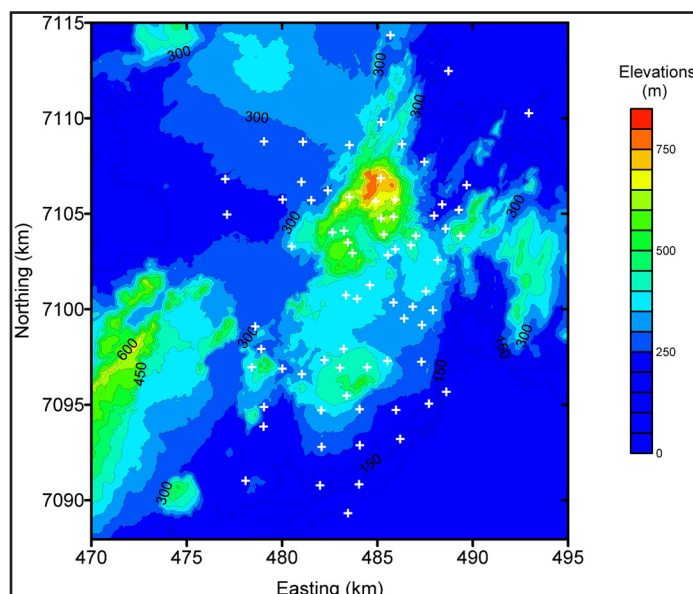


Figure 6. Hengill MT site and elevation map.

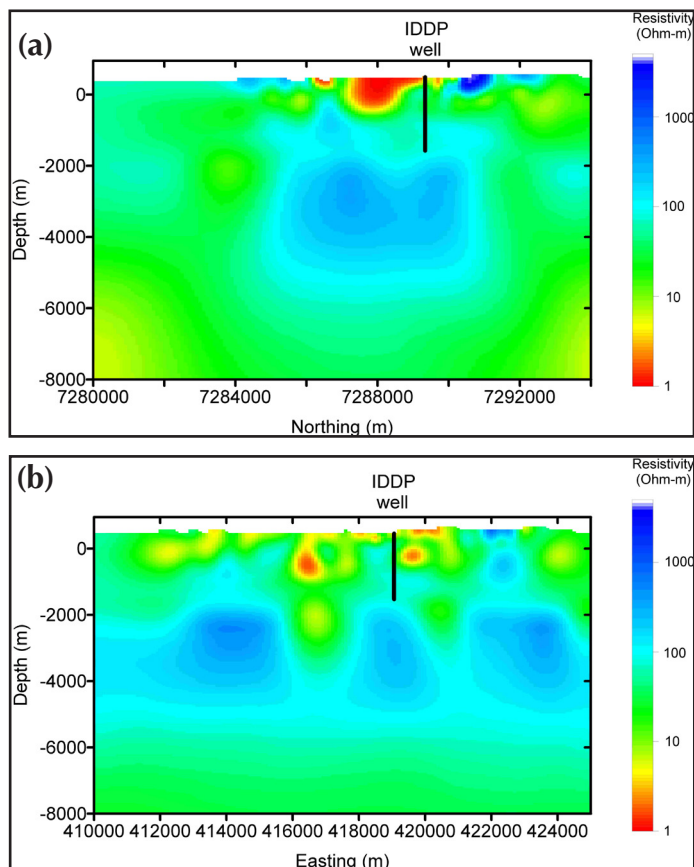


Figure 4. Resistivity cross-section at (a) Easting = 419,033 m, and (b) Northing = 7,289,380 m (the IDDP well location) taken from the 3D resistivity model in Figure 2.

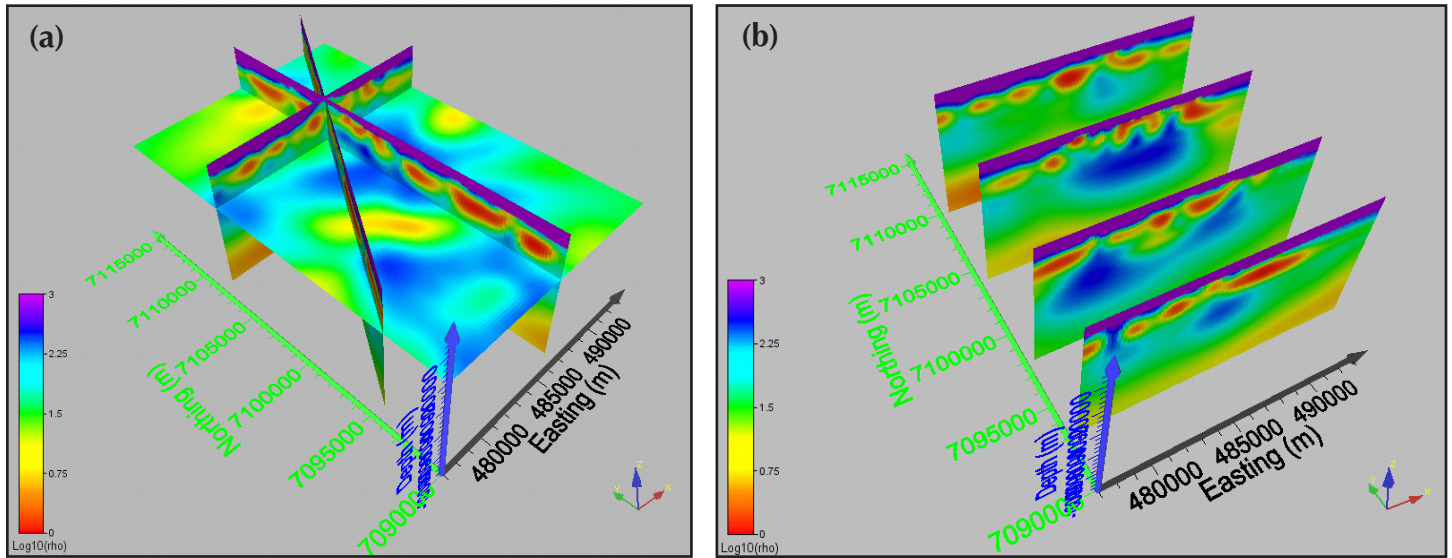


Figure 7. 3D resistivity model of the Hengill geothermal area – (a) cut-away view, (b) slices from south to north.

one of the largest high-temperature geothermal areas in Iceland. The volcanic products are mainly basalts and acidic rocks. The Hengill complex hosts three volcanic centers, and the central volcano is bisected by a 3-5 km wide and 40 km long fissure swarm in N30°E direction. Figure 6 shows elevations in 25x25 km area, and locations of 73 MT soundings (white symbols) that were used in this interpretation. Several research groups collected MT data between 2000 and 2006.

Figures 7a and 7b show a cut-away view and slices from south to north, respectively, of the 3D resistivity model obtained by the inversion. The data error misfit went from 394 to 2.62 for the final iteration.

An example of data fits for both modes of resistivity (on the left) and phase (on the right) is shown in Figure 8. Again, predicted (red curves) Zxy and Zyx, apparent resistivity and phase

data from the model show good correspondence to the field data (black symbols).

The Hengill study area can be divided into two major complexes, one in the southwest and one in the northeast. Unaltered cold rocks have high resistivities while alterations with smectite and zeolites at low temperatures make rocks less resistive. At higher temperatures, clays contain more chlorite (or illite in acidic rocks), and other alteration minerals (e.g., epidote) are present, which causes again increase in resistivity. The inverted model identifies two low-resistivity layers. The nature of the uppermost low-resistivity layer and the increasing resistivity below is due to hydrothermal mineral alteration as discussed earlier. The nature of the deep low-resistivity layer is not yet well understood. Hengill MT dataset was previously inverted using WSINV3DMT (Arnason et al., 2010), and the models agree in large-scale features. Our model offers more detailed resistivity distribution as a function of depth and spatial distances. This dataset also clearly illustrates the importance of 3D imaging. Field data show strong three-dimensionality below 1 Hz, and in areas around calderas for all frequencies, and 2D inversions were unable to fit measured data.

### Conclusions

3D MT inversions of Krafla and Hengill data sets showed that this approach is very promising in imaging geothermal reservoirs in a single self-consistent manner, and that knowledge of the subsurface electrical resistivity can contribute to a better understanding of complex geothermal systems. Resistivity in geothermal areas is governed not only by presence of fluid and temperature, but also by hydrothermal alteration products, since they contain clays. Both Krafla and Hengill geothermal complexes exhibit resistivity responses similar to other high-temperature geothermal areas. The highly resistive near

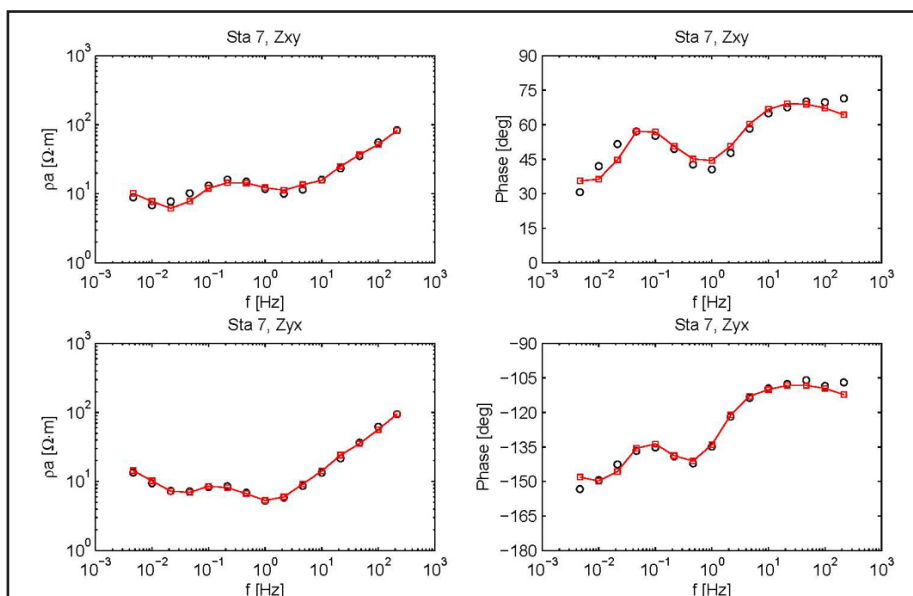


Figure 8. Example of data fits for the 3D resistivity model shown in Figure 7. Calculated (predicted) data are shown as red curves, while the field data are shown with black symbols.

surface layer represents unaltered cold rocks, below which a low-resistivity cap delineates the smectite-zeolite zone and below this cap is a more resistive epidote-chlorite zone, also called the resistive core. Resistivities in the upper 1-2 km do not correlate with lithology but with alteration mineralogy. The deep low-resistivity zone in Krafla, which depth varies, appears to be connected to shallow structure through vertical structures, “chimneys”. The resistivity images at the IDDP well location show high resistivity most likely due to epidote-chlorite geology. However, an intrusive low-resistivity feature coming up from depth, was imaged about 2 km to the northwest of the well, and has been interpreted as a magma reservoir. A possible explanation for the magma encounter at the IDDP well is that lateral pathways or fissures are connecting the magma chamber to the well. The MT response to magma pathways at such scales is not observable in the data.

## Acknowledgements

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