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A STUDY OF THE KRAFLA VOLCANO USING GRAVITY, MICRO EARTHQUAKE AND MT DATA

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ABSTRACT

Some recent studies have been done in order to understand the deeper structure of the Krafla volcanic complex and its geothermal system. The studies comprise an extensive Magneto-Telluric survey and a passive seismic survey. The Magneto-Telluric survey was carried out by two groups, a group from Duke University, North Carolina in the summers of 2004 and 2005 and a group from Moscow State University and ÍSOR in the summer of 2006. The seismic survey was carried out in 2004 and 2005 by the Duke group and another group from University of North Carolina.

The Bouguer gravity map of the Krafla area has been reviewed and interpreted. It is suggested that the gravity map shows a buried inner caldera inside the caldera seen on surface. It is further suggested that both calderas are torn apart by a WNW-ESE trending oblique transform graben filled with hyaloclastite. 1D (layered earth) interpretation of the Magneto-Telluric soundings gives consistent results, showing a conductor in the uppermost few hundred meters, reflecting clay alteration of the rocks, and a deeper conductor. The depth to the deep conductor varies greatly. It is at the depth of about 8-12 km at the margins of the survey area but domes up with two "chimneys" reaching the depth of about 2.5 km, one under and to the north of Leirhnjúkur and another under Víti and Mount Krafla. A third narrow "chimney" is seen under Leirhnjúkshraun. The two main "chimneys" roughly coincide with the magma chambers defined by S-wave shadows during the Krafla fires.

The up-doming conductors seem to be confined within the inner caldera, inferred from the gravity data. The deeper resistivity structure seems also to be influenced by the transform graben. Seismic activity, both in the Krafla fires and recorded in 2004 and 2005, is mainly confined within the inner caldera, except where it is broken up by the transform graben in the west. The depth distribution of the earthquakes shows that the seismicity is shallow and clusters right over the up-doming conductors. The seismicity extends to greater depth away from the chimneys. This is consistent with the interpretation that the chimneys reflect very hot plastic or molten rocks. The earthquakes probably reflect where the overlaying geothermal system is mining heat from the rocks at the top of the heat sources. These studies indicate that the geological structure of the Krafla volcano and its geothermal system are more complex than believed till now.

1. INTRODUCTION

The resistivity structure of the shallow crust in the Krafla geothermal area has been studied extensively by DC-resistivity methods (Schlumberger and dipole-dipole soundings and head-on resistivity profiling, in the period of 1970 to 1983) and the central-loop Transient Electro-Magnetic (TEM) method (1991 to 1999) (Árnason and Karlsdóttir, 1996; Árnason and Magnússon, 2001). These resistivity surveys have given a detailed picture of the resistivity structure and geothermal activity in the uppermost 1 km of the crust. The resistivity structure suggests a strong influence of WNW-ESE trending structures and good correlation with the volcanic history of the Krafla volcanic system.

Landsvirkjun (LV) has plans for expanding the power generation in the Krafla geothermal field. LV has also offered the Krafla area as a site for the first deep well of the Iceland Deep Drilling Programme (IDDP), with the aim of taping deep geothermal resources, below conventional drilling depths (2000-2500 m). To facilitate successful location of further production wells and especially the IDDP well, a better understanding of the deep structures of the Krafla geothermal system is important. The most promising methods for studying such deep structures are Magneto-Telluric (MT) resistivity measurements to locate heat sources and monitoring of natural seismicity to locate permeability. The MT method can probe to the depth of 20 to 50 km, and the seismicity in the Krafla area extends down to about 5-7 km.

This report discusses the results of one-dimensional (1D, layered earth models) interpretation of MT soundings made in the years 2004 to 2006. A qualitative interpretation of gravity data (Bouguer map) collected in the years 1976 to 1984 (Johnsen, 1995) is made. The interpretation of the gravity data and the distribution of micro-seismicity, recorded during the Krafla fires and in the summers of 2004 and 2005, are compared to a 3D model compiled from the 1D models of the MT soundings. It is based on a report from ISOR – Iceland GeoSurvey (Árnason et al. 2007).

2. GEOLOGICAL SETTING AND GRAVITY DATA

A very comprehensive description of the geological structure and the volcanic history of the Krafla volcanic system have been given by Saemundsson (1991). The Krafla volcanic system consists of a central volcano and a NNA-SSW trending fissure swarm running through it. Generally speaking the central volcano is characterised by gently sloping topographic high with a caldera in the middle. The caldera has been associated with an eruption producing semi-acidic welded tuff about 110000 years ago.

An extensive gravity survey was carried out from 1967 to 1984, covering the Krafla area and its surroundings (Johnsen, 1995). Figure1 shows a Bouguer gravity map based on these data (red to blue background colour). The average density of 2.49 g/cm^3 was used for the Bouguer reduction and the map has been de-trended by subtracting long wavelength background. Figure 1 shows that there is an impressive gravity high associated with the Krafla central volcano. This is most naturally explained by massive intrusions in the roots of the volcano and its lava shield. There is a distinctive gravity low under and to the east of Gaesafjöll.

Figure 2 shows a de-trended Bouguer map of the Krafla volcano and its immediate surroundings (note that Bouguer values and colours are different from Figure 1 because different background field is subtracted). The figure shows that there is a relative gravity low within the caldera. Superimposed on the gravity low is a gravity high at Leirhnjúkur. This probably reflects intrusions and a magma chamber. The caldera is transacted by two more or less linear gravity lows. One is along the part of the fissure swarm that was active in the Krafla fires (bounded by green lines on Figure 2). The other is ESE-WNW trending from Mount Jörundur in the SE and to the valley Gaesadalur (south of Gaesafjöll) in the NW. Where these anomalies would cut through the caldera rim, it is not visible.

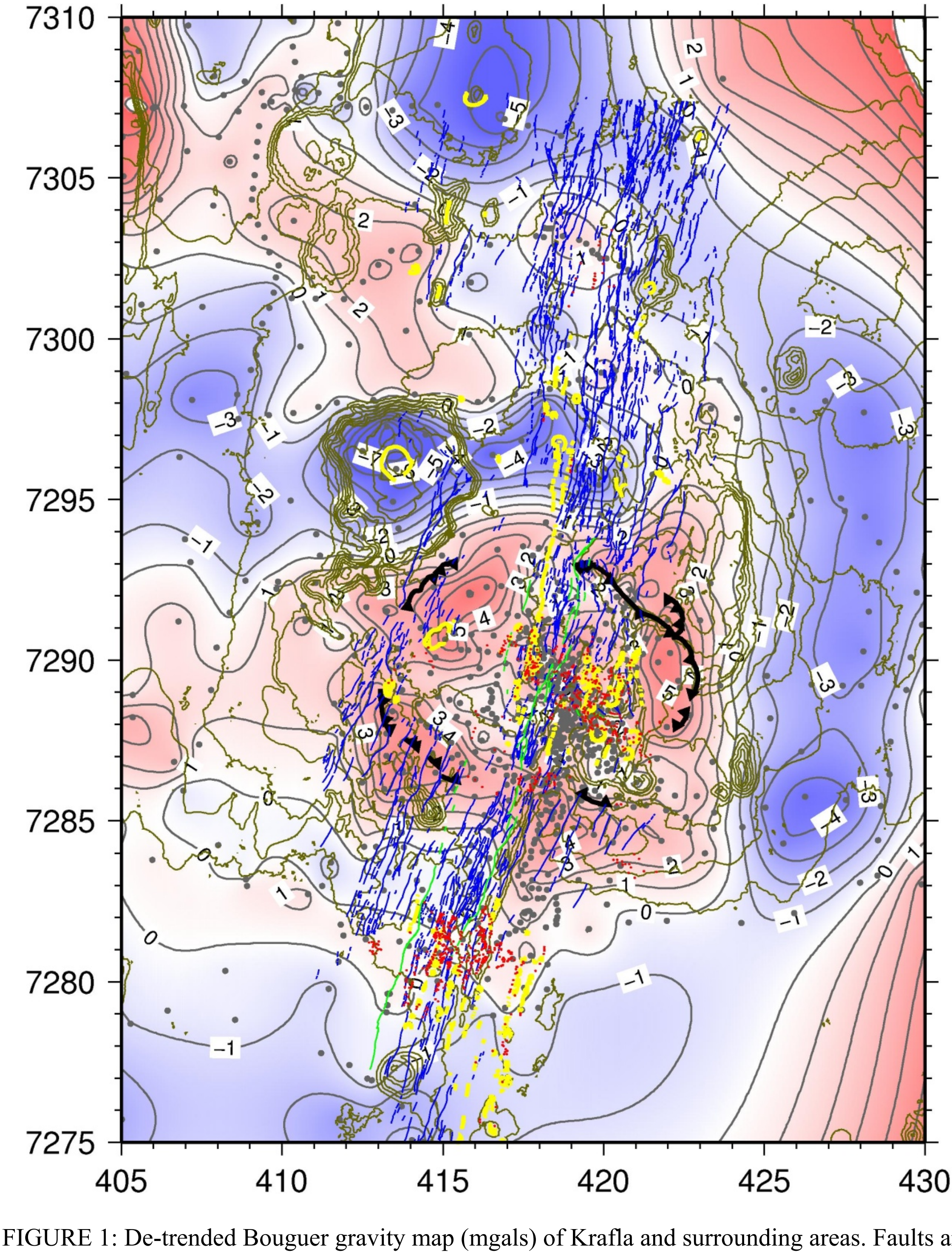

FIGURE 1: De-trended Bouguer gravity map (mgals) of Krafla and surrounding areas. Faults and fissure (blue), the caldera (hedged black lines) eruptive fissure and craters (yellow) and geothermal surface manifestations (alteration, hot springs and fumaroles, red). Boundaries of the part of the fissure swarm that was active in Krafla fires are shown as green lines. The topography (elevation contours) is shown with brown lines

Figure 2 shows other interesting features. There are gravity highs at and inside the caldera rim in the southwest, northwest and east. These high gravity anomalies are bounded by steep gradients towards a gravity low in the centre of the caldera, which is filled with less dense rocks. In the eastern part of the caldera the gradient co-insides with arc like eruptive fissures from Hólseldar, about 2000 years ago (Saemundsson, 1991). Some might like to argue that the high gravity at and inside the caldera rim is

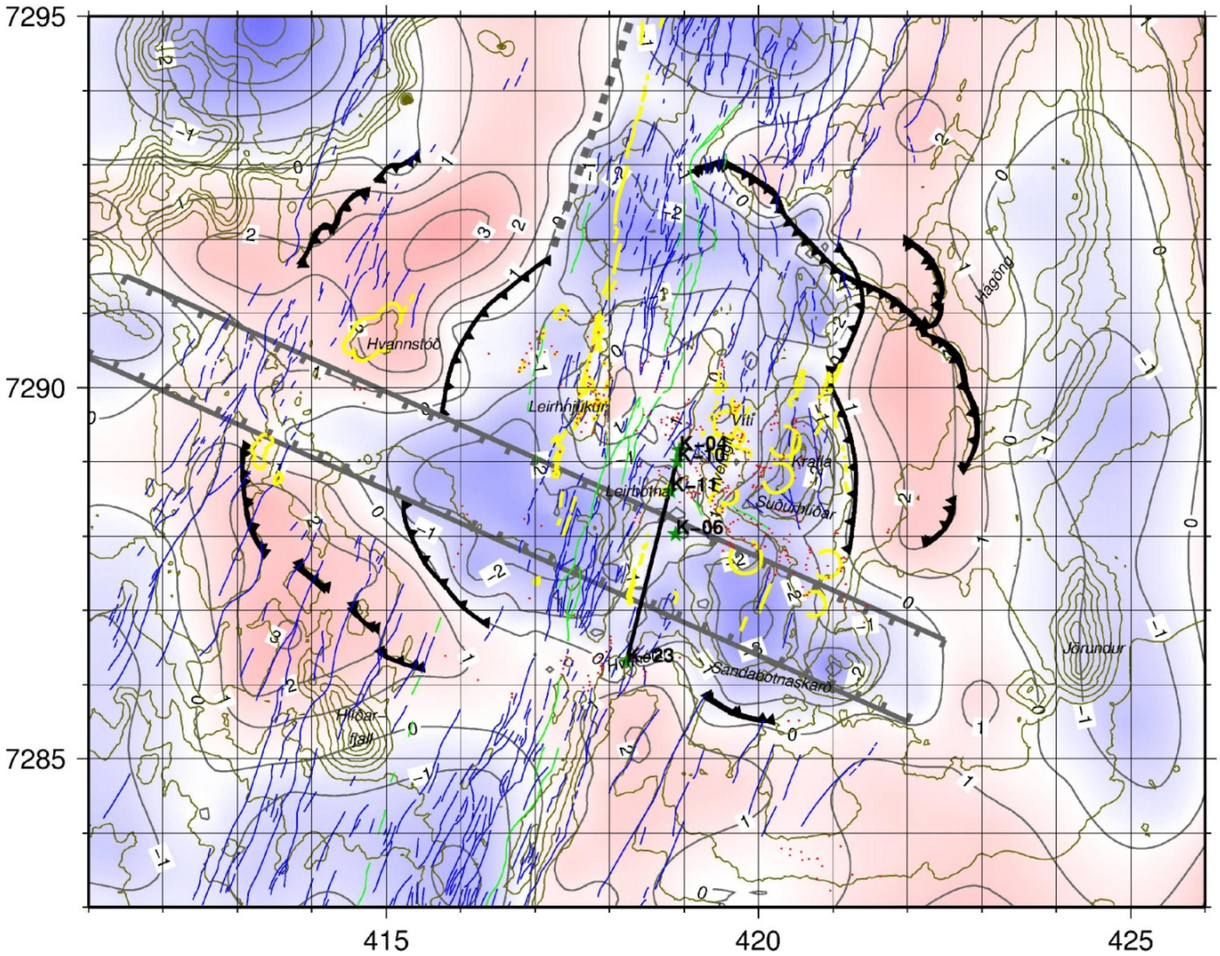

FIGURE 2: De-trended Bouguer gravity map (mgals) of Krafla volcano. Geological information is the same as on Figure 1. The rims of the outer caldera and the inferred buried inner caldera are shown (hedged black lines). An inferred ESE-WNW transform graben is shown (gray fault lines) A linear density contrast in the fissure swarm to the north is also shown (gray broken line). The location of a lithological section in Figure 3 is shown (black line) and the wells on which it is based (green stars)

due to dense intrusions, but the steep gradients clearly show that the density contrasts are at shallow depth. This strongly suggests that there is another caldera buried inside the caldera seen on surface.

The outer caldera has been dated as being 110000 years old. In the 30000 years between its formation and until glaciation, the outer caldera has been mostly filled with lava flows. The inner caldera was probably formed after the area was covered with ice. It was later filled and buried with hyaloclastite of considerable lower density than the subaerial lavas filling the outer caldera, producing the gravity low. The inner caldera must be older than Sandabotnafjall which was formed some 40000 years ago (Saemundsson, 1991) because it lies over the caldera rim. The inner caldera was therefore formed sometime between 80000 and 40000 years ago.

The gravity data indicate that the geological structure of the Krafla volcanic complex is more complicated than has been believed. There is no evidence of the inner caldera on the surface (except may be the volcanic fissures in the eastern slopes of Krafla). It is totally filled and buried by younger volcanic products. There is little or no evidence of inner caldera found in deep wells because they are all inside it or at its rims. There is, however, some evidence of the ESE-WNW oblique transform graben from drilling. Figure 3 shows a lithological section across the inferred transform graben (Ármannsson et.al., 1987). The wells on which the section is based and the location of the section is shown in Figure 2. The section shows 600-700 m thicker pile of hyaloclastite with interbedded lava flows within the transform graben (well K-06) than north of the graben (wells K-08, K-10 and K-04). This lends support to the idea that the calderas are indeed transected by an ESE-WNW graben.

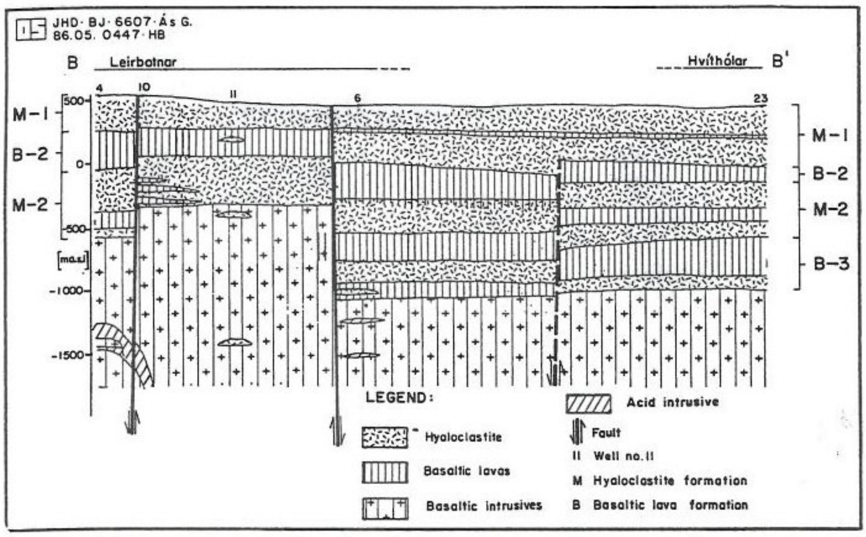

FIGURE 3: Lithological section based on wells, from north (left) to south (right) within the Krafla caldera. For location see Figure 2 (from Ármannsson et.al. 1987)

3. SEISMIC DATA

During the tectonic and volcanic activities in the ninety seventies and eighties the Krafla volcano and its fissure swarm was very seismically active. The earthquake activity was monitored and recorded by a seismic network operated by the Science Institute at the University of Iceland (Einarsson, 1991; Sandford and Einarsson, 1982). In the year 2004, two experiments were performed in the Krafla area. A group from the University of North Carolina, led by Prof. Jose Real deployed 20 portable seismic stations for about two months in the Krafla area to record micro-seismicity. A second group, from Duke University North Carolina, led by Stephen Onacha (a PhD student) and Prof. Peter Malin, deployed further 20 seismic stations and made 50 MT soundings to study the deep resistivity structure. In a second campaign, in 2005, the Duke group recorded micro-seismicity for one and a half month and installed two seismometers in boreholes and recorded for about six months.

Figure 4 shows the epicentres of all earthquakes considered in this study. Epicentres of earthquakes in the Krafla area recorded between 1974 and 1988 (1445 quakes) are located with horizontal uncertainty less than one km (Einarsson and Brandsdóttir, pers. comm.). The data from 2004 and 2005 were recorded by dense networks on top of the volcano (330 quakes). This means that the latter are located with much better accuracy. The figure shows that the earthquake activity was mainly confined within the inner caldera, except where the calderas are torn by the WNW-ESE transform graben in the west. The earthquakes seem to cluster in two WNW-ESE trending areas, one inside the boundaries of the resistive core in NE and another one where the transform graben runs through the calderas. Most of the earthquakes occur between 1 and 3 km depth. There is a tail of quakes at greater depths, mainly from the Krafla fires. Closer inspection shows that these are mainly events outside the inner caldera. Of the earthquakes recorded 2004 and 2005 there are only a five deeper than 3 km and they are all outside the inner caldera.

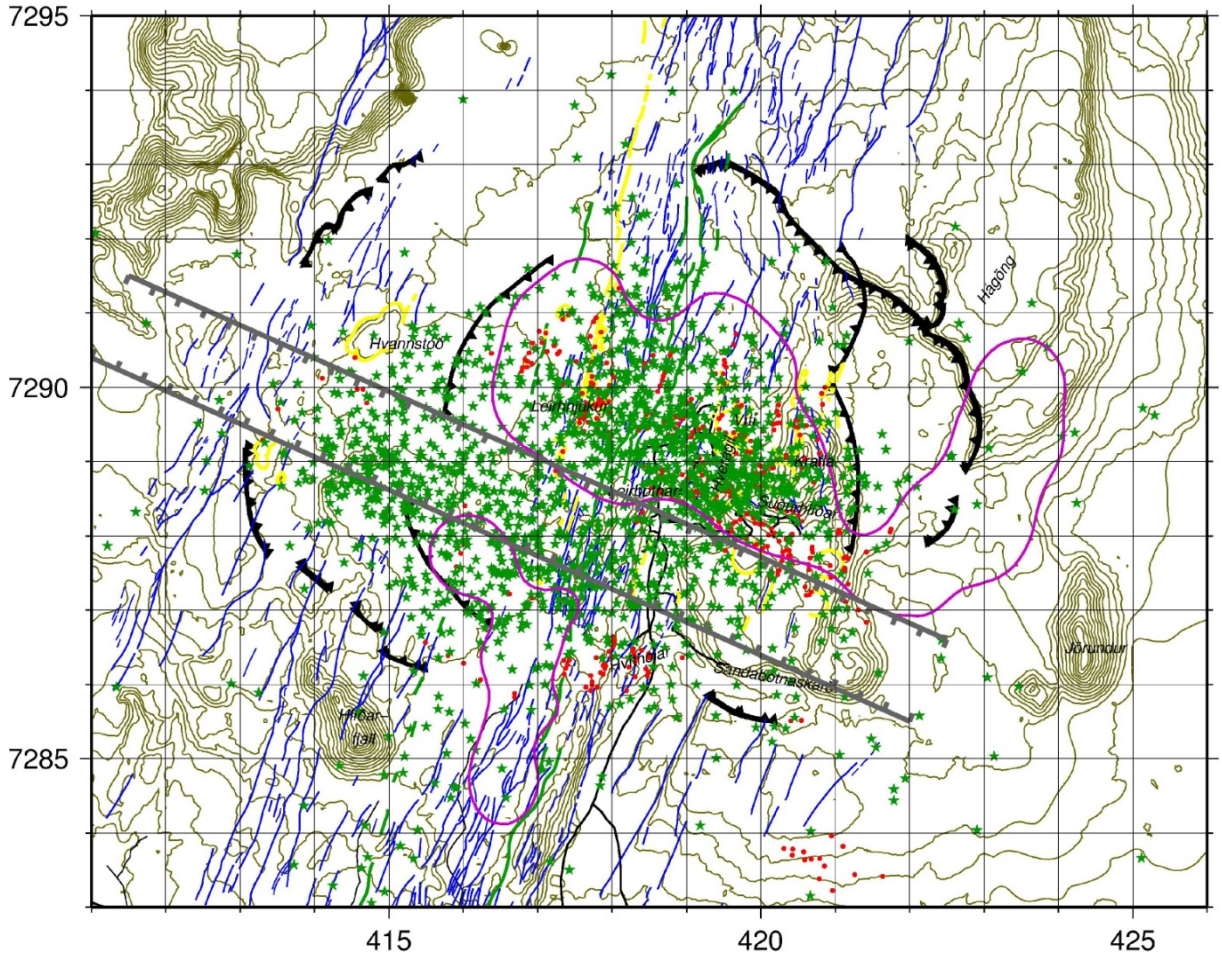

FIGURE 4: Epicentres of all earthquakes (green stars) in the Krafla area considered in this study. Faults and fissure are shown (blue), the two calderas (hedged black lines), the inferred transform graben (gray fault lines), eruptive fissure and craters (yellow) and geothermal surface manifestations (alteration, hot springs and fumaroles, red). The purple lines show the boundaries of the resistive core at 200 m above sea level as seen by TEM soundings

Earthquakes occur when rocks in the crust break under strain. At high temperatures, about 600-700°C, the basaltic rocks start to become ductile and creep under strain (they can though break if the strain rate is very high). This is called the brittle-ductile transition. At still higher temperatures, 1100-1200°C, the rocks are partially or totally molten and do not break under strain.

The depth distribution of earthquakes therefore gives information on prevailing temperature. The fact that there are almost no earthquakes observed in the inner caldera at depths greater than 3 km is most naturally interpreted in such a way that below that depth the rocks are not brittle. This indicates that at depths greater than 3 km the temperature is at least 600°C. Earthquake waves, radiating from the hypocentre, comprise two types of waves, pressure waves (P-waves) and shear waves (S-waves). The P-waves travel both through solids and liquids. The S-waves cannot travel through liquids and are highly attenuated in partially molten rocks. Analysis of the earthquake data from the Krafla fires revealed that S-waves could not penetrate through some volumes within the Krafla volcano. This was interpreted such that these volumes hosted magma chambers with molten rocks in the depth range of 3 to 7 km (Einarsson, 1991, 1978). Figure 5 shows the boundaries of the inferred magma chambers. This interpretation is consistent with the lack of earthquakes below 3 km depth. The presence of the S-wave shadows right below the lower boundary of the seismicity must mean that the temperature rises from about 600°C and to about 1100°C in a very narrow depth range.

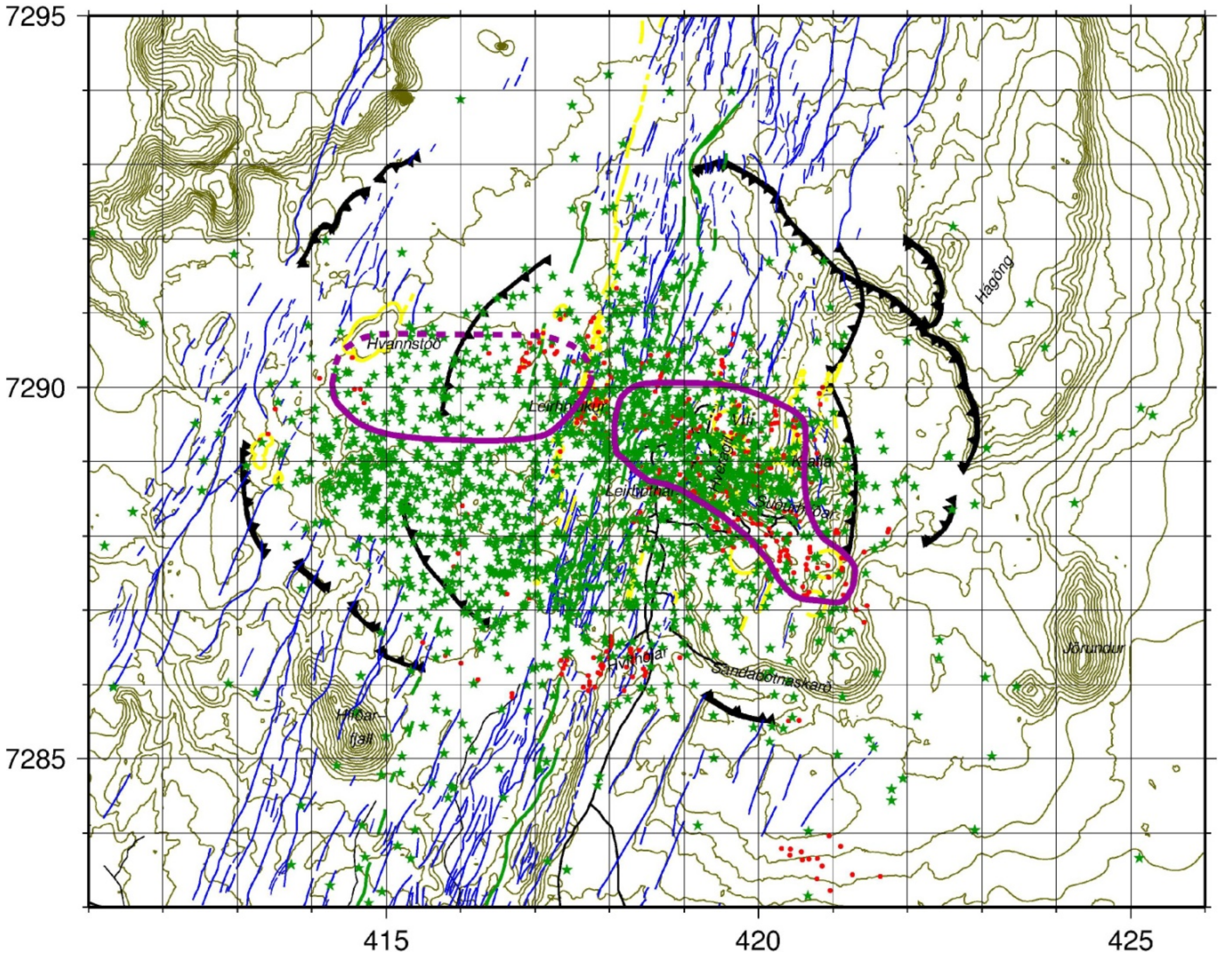

FIGURE 5: Earthquake epicentres (green stars) and boundaries of S-wave shadows (purple lines) observed during the Krafla fires (reproduced from Einarsson, 1991). Other geological features are the same as on previous maps

4. MT SURVEY

An MT survey has been carried out in the Krafla geothermal field. This was done in three campaigns. In the summer of 2004 a group from Duke University, led by Stephen Onacha made 50 soundings. The Duke group made a second visit in 2005 and made further 58 soundings. The distribution of the MT soundings from 2004 and 2005 is very uneven and it was therefore decided by LV to complete the coverage of the Krafla geothermal field by adding 55 MT soundings. This was done by a group of MT specialists from Moscow State University (MSU) and ISOR employees in the summer of 2006. The total number of MT soundings made in the area is therefore 163.

4.1 Processing and interpretation of the MT data

The MT data were collected with equipment from Phoenix, using the remote reference technique. The basic data processing of time series to produce impedances and tippers (as functions of periods) was done with software provided by Phoenix and the results written to files on the standard EDI format.
The MT method, like all resistivity methods where the electric field is measured in the surface, suffers a problem called the telluric shift problem. The reason for this is that local resistivity anomalies at the sounding site influence and distort the electric field, independent of frequency. The result of this is that the apparent resistivity values have an unknown multiplier (shift of logarithmic values). The TEM soundings do not suffer this problem because they measure magnetic induction in a receiver coil (or

loop). By interpreting together TEM and MT soundings made nearly at the same place, the TEM data can be used to determine the unknown multiplier of the MT apparent resistivity (see Figure 6).

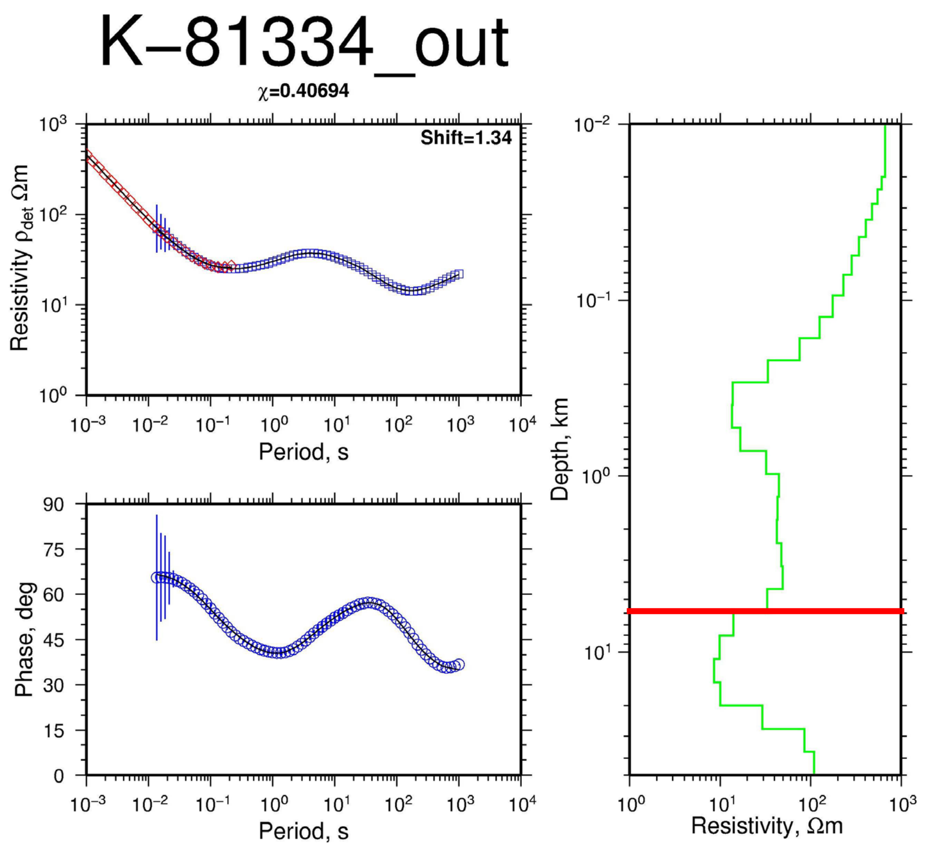

FIGURE 6: A typical result of a joint inversion of TEM and MT soundings. Red circles are the measured TEM apparent resistivity values and the blue circles are the apparent resistivity and phase values derived from the determinant of the impedance tensor. Black solid thin lines are calculated responses of the model to the right. In order to make the MT apparent resistivity tie in with that of the TEM, the MT apparent resistivity values have to be divided by a shift parameter of 1.34 (top right corner of the apparent resistivity panel)

The 1D inversion presented in this report is a so-called "minimum structure" or Occam's inversion. The soundings are fitted by the response of models with many layers (30-40) with constant thicknesses, increasing exponentially with depth. The variation in resistivity values is damped in order to get as smooth models as possible. The unknown parameters that are determined in the inversion are the resistivities of the layers and the shift multiplier.

A total of 72 out of the 108 soundings made by the Duke group have been interpreted and 53 of the 55 soundings made in 2006. The total number of soundings interpreted is 125 (locations in Figure 7). All the resistivity models resulting from the 1D inversion have similar structure to the one seen on Figure 6. An upper conductor (low resistivity) is seen with the upper boundary at variable depths, from near surface and to some hundred metres and the thickness of some hundreds of metres. It is underlain more resistive rocks. At greater depth a second deep conductor is seen with upper boundary at the depth of 2.5-12 kilometres (marked with red line on Figure 6) and thickness of some tens of kilometres. The deep conductor is again underlain by higher resistivity.

The shallow conductor is the low-resistivity cap (clay cap) and the higher resistivity below is what has been called the resistive core, as seen in previous TEM surveys (Árnason and Magnússon, 2001). The shallow resistivity structure is well understood (Árnason et al., 2000). The low resistivity cap reflects clay (smectite) alteration formed in the temperature range of 100-240°C and the transition to the resistive core reflects transition from smectite to chlorite as temperature exceeds 240°C. The nature of the deep conductors is not as clear and possible explanations will be discussed later.

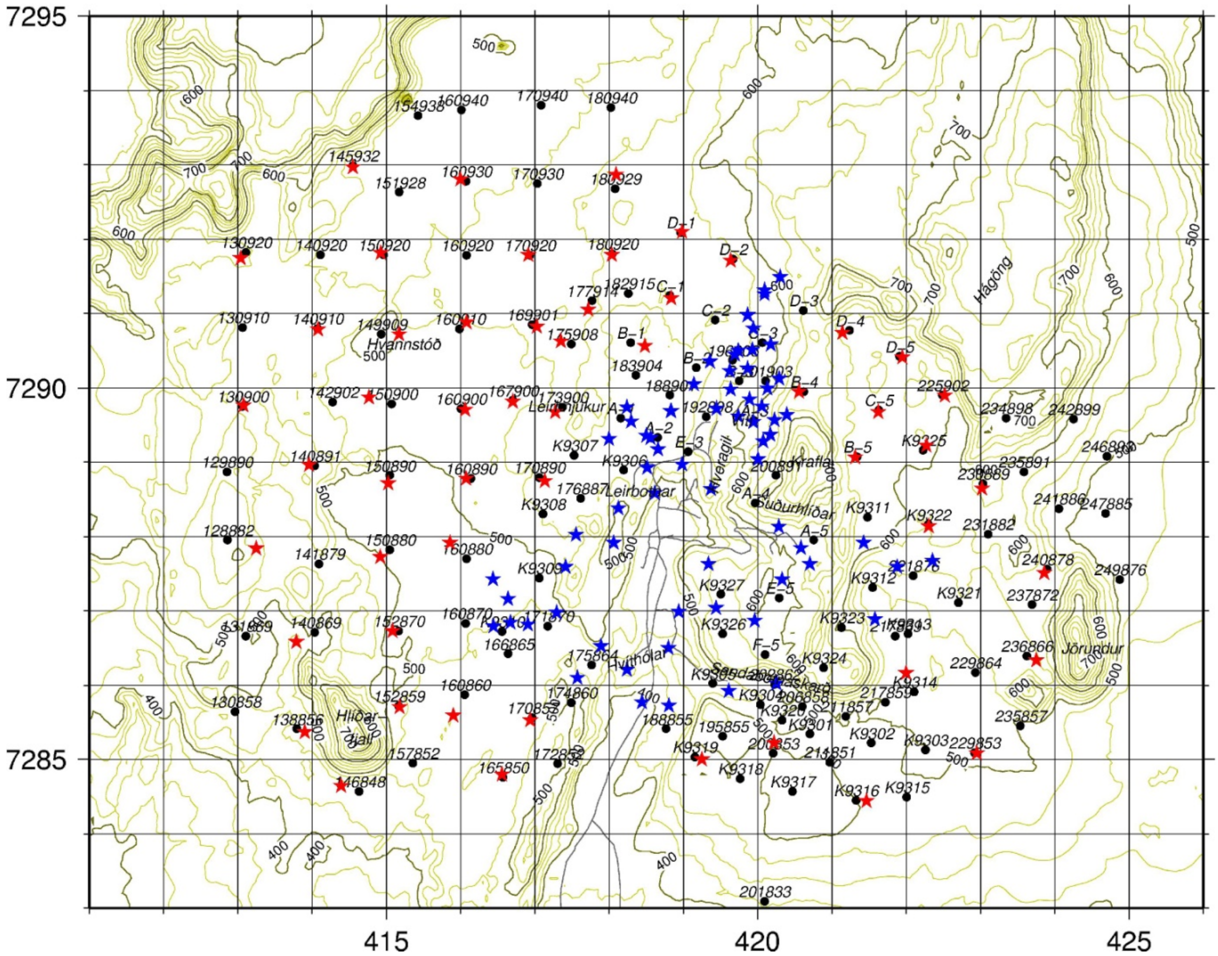

FIGURE 7: Location of interpreted MT soundings. Blue stars are soundings made in 2004 and 2005. Red stars are soundings made in 2006. TEM soundings are shown as black dots

4.2 Results of the 1D inversion; resistivity maps

The results of the joint 1D inversion of the TEM and MT data for various depths are not presented here but in Figure 8 is an example of an iso-resistivity map at 3000 m below sea level.

At the depth of about 2 km b.s.l. (2.5 km depth) the resistivity starts decreasing again within the inner caldera. These deep conductors reach closest to the surface NW of Mount Krafla, under and to the north of Leirhnjúkur and under Leirhnjúkshraun at the SW rim of the inner caldera. These deep conductors become more prominent with increasing depth but are almost entirely confined within the inner caldera to the depth of about 6 km b.s.l. Below 8 km b.s.l., low resistivity starts to spread out of the inner caldera and below 10 km b.s.l. low resistivity is seen in the whole study area.

Iso-lines of the upper boundary of the deep conductors are shown in Figure 9. The figure shows clearly how the main conductors are confined within the inner caldera inferred from the gravity data. They are found where the caldera rims can be seen in the gravity data but are absent where the caldera is torn apart in the west and south-east. The deep conductors in the NE part of the inner caldera show up as a big low resistivity anomaly at depth but with two chimneys reaching up to about 2 km b.s.l. or about 2.5 km depth.

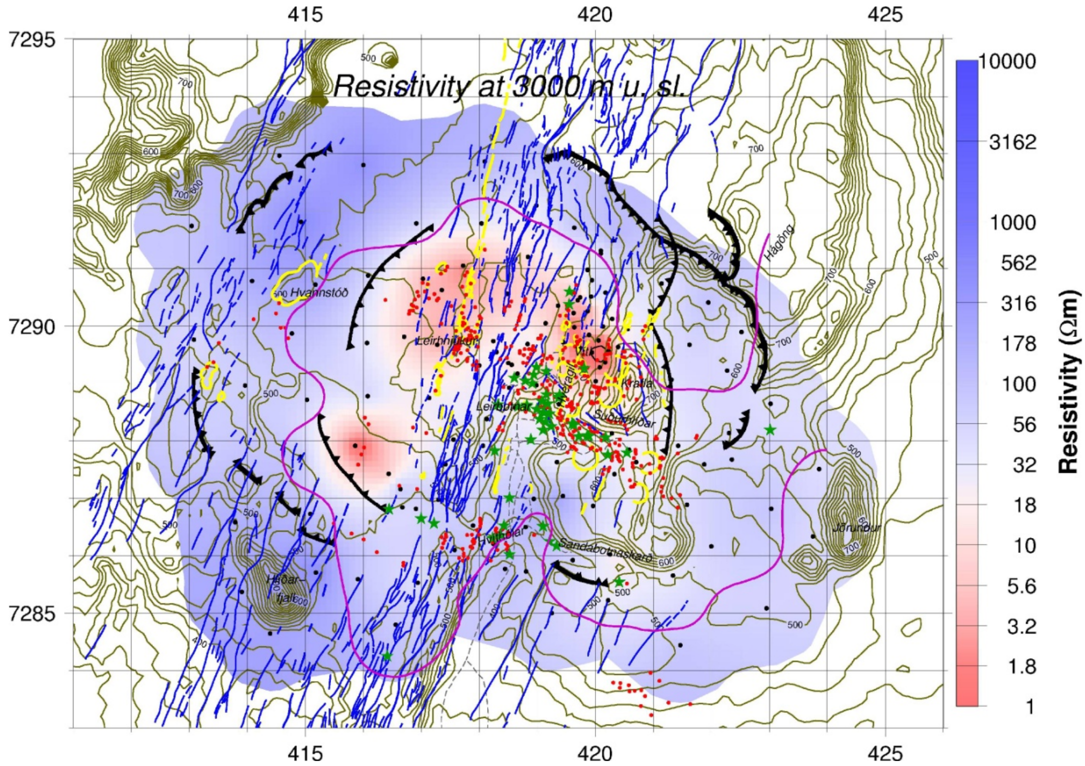

FIGURE 8: Resistivity at 3 km below sea level. The boundaries of the resistive core at 600 m b.s.l. are shown by a purple line

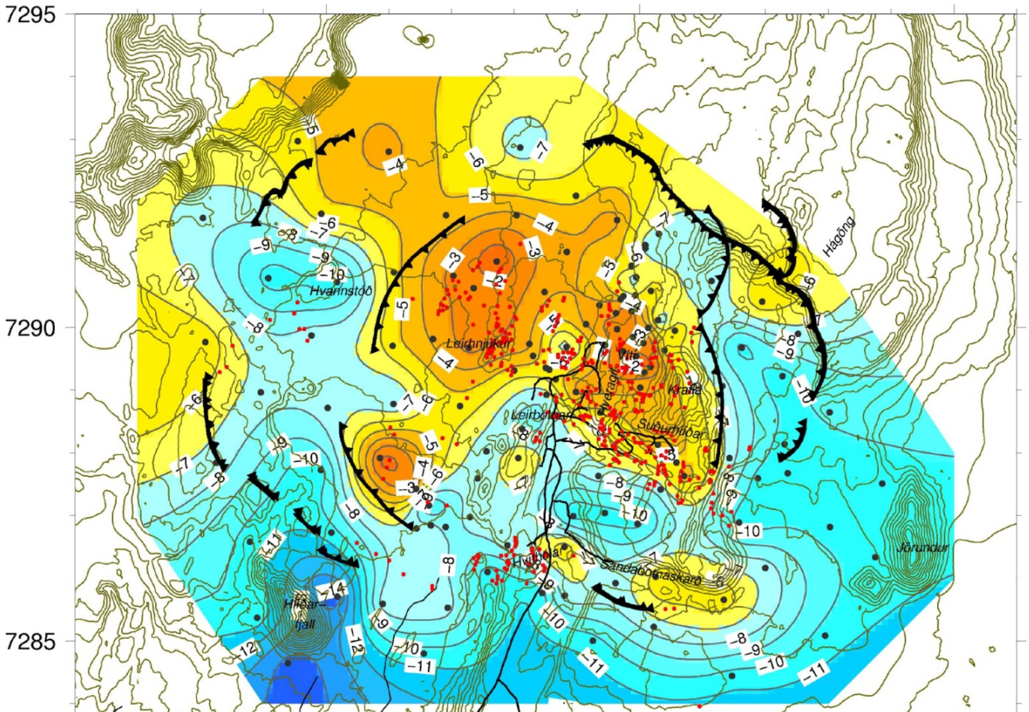

FIGURE 9: Elevation (km above sea level) of the upper boundary of deep conductors in the Krafla volcanic complex. Caldera rims are shown by black hatched lines and geothermal surface manifestation by red dots

4.3 Results of the 1D inversion; resistivity cross-sections

A total of 20 resistivity cross-sections were made, 9 W-E trending sections (AV7285-AV7293 numbered from south to north) and 11 N-S trending sections (NS413-NS423, numbered from west). Only one section is presented graphically in this paper, AV7290 (see Figure 10) as an example. All the sections showed a shallow low resistivity layer in the uppermost few hundred metres. This is the low resistivity (clay) cap and is underlain by higher resistivity (the resistive core).

The depth distribution of earthquakes (projected on the sections) showed some interesting features. Generally the quakes are concentrated above ore close to the up-doming deep conductors (as can be appreciated from Figure 10). There seems to be a correlation between resistivity at depth and the depth of earthquakes. The deeper to low resistivity the deeper are the earthquakes. The earthquakes are rare in the deep conductors

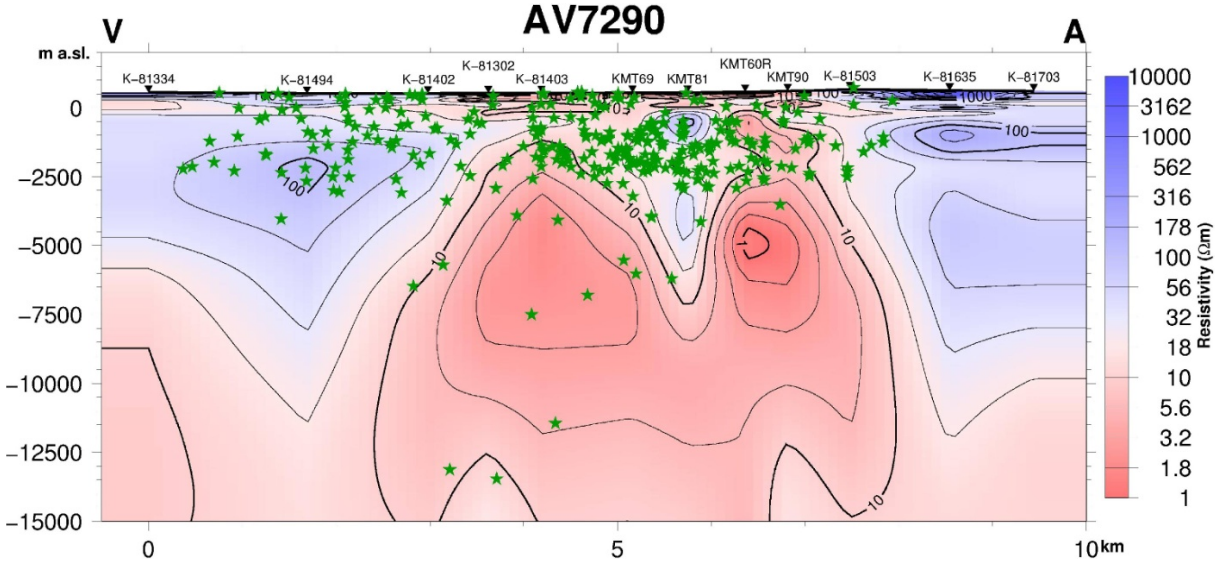

FIGURE 10: E-W cross-section AV7290. Located immediately south of line 7290 (see Figure 7). Earthquakes at distances less than 500 m are projected on the section (green stars)

4.4 What are the deeper conductors?

The shallow resistivity structure of the high-temperature geothermal systems in Iceland is fairly well understood, as discussed earlier (section 0). What makes the rocks more conductive again at greater depth and higher temperatures? What is the high conductivity reflecting? These are fundamental questions that have not been answered properly as yet.

The conductors at depth in the crust can in some cases be explained by melt but in other cases probably not. Another possible explanation could be trapped magmatic brine. Even though it is not in all cases clear what causes the low resistivity anomalies at depth in the crust, all realistic explanations assume high temperatures. If the low resistivity is caused by trapped magmatic brine, the temperature has to be above the brittle-plastic transition, i.e. above 600-700°C. If the low resistivity is due to melting, as is the case in at least parts of the Krafla volcano, the temperature must be about 1200°C. The conclusion is that even though the cause of localised good conductors in the crust is not always clear, they can, in relatively good confidence, be assumed to be heat sources for hydrothermal systems.

5. COMBINED RESULTS AND CONCLUSIONS.

In this study three independent data sets are considered, i.e. gravity data, seismic data and TEM/MT data. Each of the data sets indicates the presence of an anomalous ring structure within the caldera visible on the surface.

Figure 11 shows the combined results of the interpretation of the Bouguer gravity map, i.e. the inner caldera and the oblique transform graben. The figure shows how the crustal conductor dome up in the northern part of the caldera and are abruptly cut off at the northern margin of the WNW-ESE rift graben. The figure also shows that there is a shallow conductor found where the SW rim is seen south of the transform graben. It should be noted here that this anomaly is only sustained by two soundings and should be confirmed by making the TEM/MT coverage denser in this area.

Given that the relatively shallow conductive bodies reflected intruded magma bodies (which is known to be the case in the northern part of the caldera) then **FIGURE** Figure 11 indicates that intrusion have, mainly taken place within the inner caldera for the last tens of thousands of years. The absence of conductors in the transform graben indicates that intrusions are less favoured there. The reason for this is not clear.

The seismicity also indicates an anomalous structure within the outer caldera. Figure 4 shows that during the Krafla fires and more recently, the seismic activity is mostly within the inner caldera and west of it where it is transected by the transform graben. Figure 11 also shows the boundaries of the magma chambers (S-wave shadows) as mapped by Einarsson (1978 and 1991). It is seen that the up-doming of the conductor under Víti and Mount Krafla corresponds closely to the boundaries as defined by the S-wave shadow. The agreement is not as good for the western magma chamber. The S-wave shadow is shown to extend considerably to west of Leirhnjúkur and not as far to the north as the low resistivity anomaly under and to the north of Leirhnjúkur. This discrepancy might be due to lower spatial resolution of the S-wave shadow than in the MT data.

Figure 11 further shows the locations of some centres of uplift or subsidence (blue stars) estimated from ground deformation measurements during some inflation and deflation episodes in 1984 (Tryggvason, 1986). The deformation was consistent with a point pressure source at 2.6 km depth. Satellite Radar Interferometry, geodetic measurements and microgravity data show that the magma chamber(s) is deflating (Sigmundsson, 1997, Dalfsen et.al, 2005). The figure shows the estimated centre of subsidence (red star) that took place between 1992 and 1995 (Sigmundsson, 1997). Again the crustal deformation was consistent with a point sours at the depth of about 2.8 km.

The depth to the low resistivity bodies in the northern part of the inner caldera is about 2.5 km, in good agreement with the depth to the magma chamber(s) as estimated from ground deformation. The locations of the ground deformation centres seem to be in between and close to the southern edges of the S-wave shadows and the tops of the up-doming conductors. This might indicate that there is a structural weakness south of the magma chamber(s) and the uppermost two kilometres of the crust behave as a stiff plate on top of the magma camber(s).

The depth distribution of the earthquakes is consistent with the interpretation that the chimneys reflect very hot plastic or molten rocks. The earthquakes probably reflect where the overlaying geothermal system is mining heat from the rocks at the top of the heat sources.

As mentioned earlier, the three independent data sets considered here support each other remarkably well in consistently revealing anomalies within the Krafla volcano. These anomalies are most naturally explained by assuming some new geological features which are hardly or not visible on the surface. The data indicate that there is a buried inner caldera and a WNW-ESE oblique rift graben transecting both calderas. Both the inner caldera and the transform rift are filled with hyaloclastite and the covered with younger formations.

These studies therefore indicate that the geological structure of the Krafla volcano and its geothermal system is more complex than believed till now.

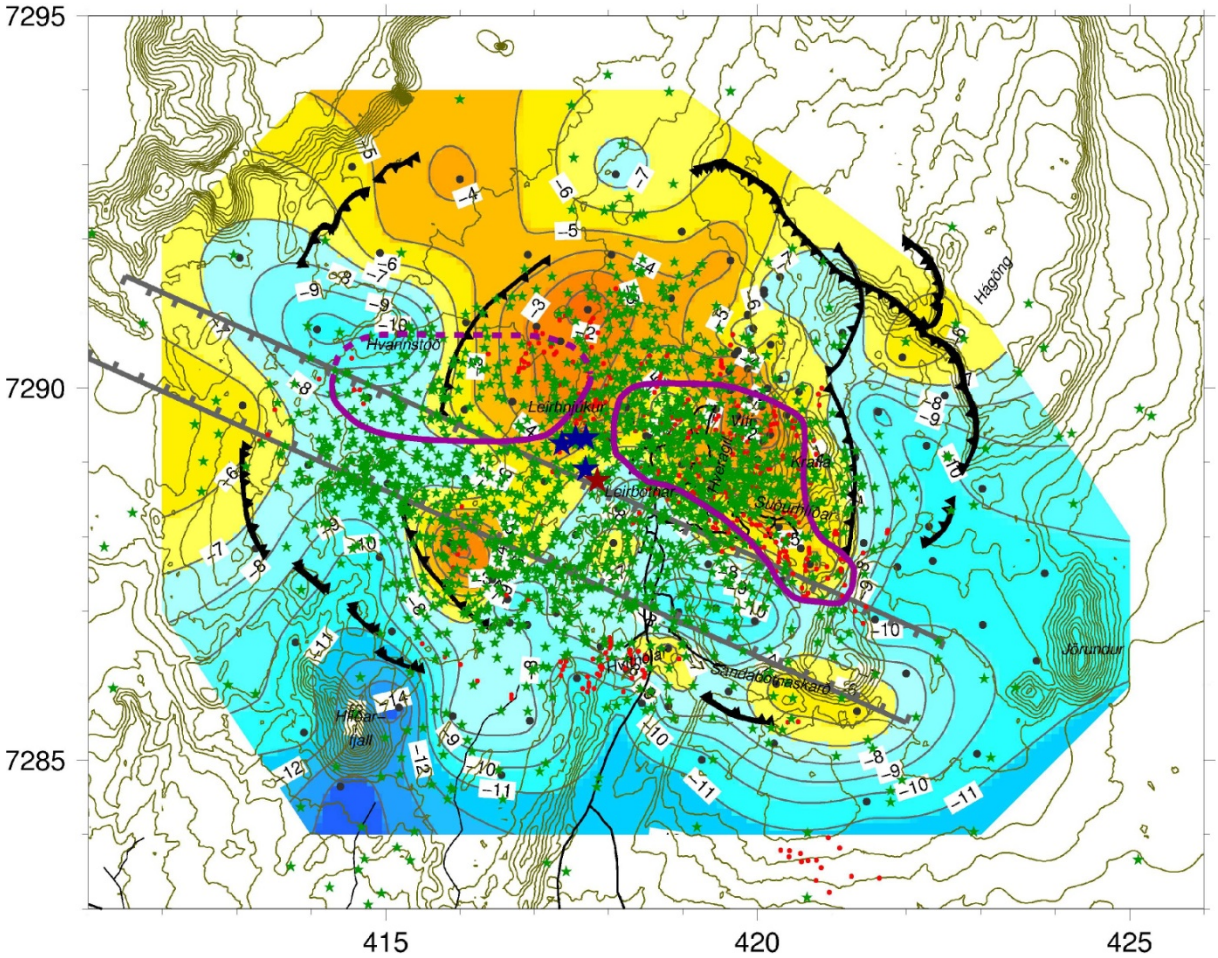

FIGURE 11: Elevation (km above sea level) of the top of conductors within the crust of Krafla, geological features inferred from gravity data (the inner caldera, black hedged lines and the oblique rift graben, gray fault lines), epicentres of earthquakes (green stars), boundaries of S-wave shadows (purple lines), centres of crustal deformation in 1984 (blue stars) and centre of subsidence from1992 to 1995 (red star)

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