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MICROEARTHQUAKE SURVEY AT THE BURANGA GEOTHERMAL PROSPECT, WESTERN UGANDA

Norbert Ochmann[#], Michael Lindenfeld[#], Paula Barbirye[*] and Christopher Stadtler[#]

[*]GSMD, Geological Survey and Mines Department, P.O. Box 9, Entebbe, Uganda
[#] BGR, Federal Institute for Geosciences and Natural Resources, Stilleweg 2, D-30655 Hannover, Germany
e-mail: norbert.ochmann@bgr.de

ABSTRACT

The BGR supports the Government of Uganda in the geoscientific investigations of the Buranga geothermal prospect since 2004. The objective of the project is to raise the knowledge about Buranga to a level (pre-feasibility status) that can be the base for planning of exploration wells.
Geochemical findings, which have been achieved in the framework of the joint project, proofed the existence of a magmatic body that in all probability serves as the heat source of the hot springs. Hence the task of active ground geophysics was detecting and delineating this magmatic intrusion. The known high seismicity (about 300 local earthquakes per month) suggested that Buranga provides excellent preconditions to apply seismology.

From May 2005 to August 2006 up to 15 seismological stations were deployed to record local earthquakes in the Buranga region. The tomography of the seismic data is expected to yield two results:

- delineation of the magmatic intrusion at depth and
- delineation of the active faults/fault systems by an exact localization of the hypocenters.

First results will be presented here. They will be reinforced and better elaborated when all the data will be included. Low velocity anomalies, supposed to represent the magmatic intrusive bodies, are shown in horizontal and vertical sections and are constituted at depths levels even below 15km.

INTRODUCTION

With climate protection and sustainable development of natural resources as objectives, the German government has initiated a program for the support of renewable energy projects, specifically within the scope of Technical Cooperation. Within the framework of this program, the GEOTHERM subprogram for the support of geothermal energy projects was begun in early 2003, implemented by BGR (German Geological Survey).
The objective of the program is to promote the use of geothermal energy in partner countries by kicking off development at promising sites. The program supports partner countries worldwide, preferably in areas with high geothermal potential. The aim is to minimize the high initial investment risk associated with the development of geothermal resources.

In Uganda power generation is dominated by hydropower. Uganda has a total generating electricity capacity of 397 MW (2004), mainly generated by a single source on the River Nile (380 MW), the rest by few small hydropower plants. The electrification rate is very low, with grid access of only 9% for the whole country and 3% in rural areas. Additional 1% of the population provides itself with electricity using generators, car batteries and solar PV systems. The electricity demand rate is estimated to be growing at a rate of 7-8% per annum resulting in a need for an increasing power generation.

The Government of Uganda is studying ways to meet the increasing energy demand by other indigenous energy sources. Geothermal energy presents a high priority alternative to hydropower. Uganda's potential for geothermal power generation is estimated at about 450 MW. The most promising geothermal areas are Buranga, Katwe and Kibiro (Bahati et al., 2005) which are situated in West-Uganda in the Albertine Rift, a part of the western branch of the East African Rift System.

Since the end of 2004 BGR, through the GEOTHERM program, supports the Government of Uganda in the geoscientific investigations at the Buranga geothermal prospect. The objective of the project is to raise the knowledge about Buranga to a level (pre-feasibility status) that can be the base for planning of exploration wells. The Ugandan project partner is the Geological Survey and Mines Department (GSMD).

SURVEY AREA

The Buranga hot springs are situated in the Albertine Rift (western branch of the East African Rift) in the Semliki National Park in Bundibugyo district to the west of the Rwenzori Massif. The national park extends to the north and west of the Semliki River, which marks the borderline to the Democratic Republic of Congo. The springs are situated in a swamp in tropical rain forest a few hundred meters westerly of the Bwamba fault, which forms the western flank of the Rwenzori and the eastern scarp of the rift respectively. At the Bwamba fault the Precambrian basement rocks of the Rwenzori Massif dip 60-65° west and strike 20-40° NNE. The Buranga hot springs consist of 37 springs with an overall flow rate of 30 l/s and temperatures up to 98.4°C.

Figure 1. The largest spring of the Buranga hot springs has deposited large amounts of travertine.

The survey area is located in a terrain that is very difficult to access. The eastern part of the study area is situated at the steeply dipping escarpment of the Rwenzori Massif (Bwamba fault). The western part of the survey area is covered by dense tropical rain forest with creeks and swamps. The hot springs are located in a swampy terrain in clearings of the rain forest. In the northern part of the survey area the rain forest is thinning out and the terrain changes to a plain covered by grass.

PREVIOUS WORK

In 1953/54 the Geological Survey of Uganda carried out a drilling program at Buranga in order to determine if geothermal power could be developed. Three or four boreholes were drilled in Buranga with depth up to 349 m (Árnason, 2003). One Borehole produced thermal water and is still flowing; in February 2005 the measured water temperature was 62°C.

In 1973 two Schlumberger soundings were executed at Buranga. The results show that the resistivities of the rift sediments decrease towards the hot springs and that the high resistive basement dips west at the Bwamba fault.

Pallister (1952) and Árnason (2003) consider that geothermal activity of the Buranga hot springs is most likely related to tectonic activity in the rift. It was observed that historical earthquakes, e.g. 20th March 1966, 17th May 1966 (both magnitude 6.1-6.3, epicenters about 30 km SW of Buranga) and 6th February 1994 incl. some after quakes (magnitude 6.3, epicenter south of Fort Portal), changed the geothermal activity of the Buranga hot springs. After the latter earthquake a new group of hot springs opened at Buranga (Gislason et al., 1994) which shows that seismological activity can open or reactivate flow paths for thermal water in the basements and sediments.

The observation that after strong earthquakes local displacements of the hot springs as well as changes of the individual flow rates had occurred suggests that the activity of the Buranga hot springs is very much related to an active fault system and that these tectonically active faults might provide the migration paths for the hydrothermal water.

Chemical analysis and geothermometry of water samples from hot springs in Buranga indicated reservoir temperatures of about 120°C, with a possible maximum of 150°C (Ármannsson, 1994). Recent isotope geothermometry indicated temperatures of 200°C (IAEA, 2003).

The GSMD compiled a soil temperature map of Buranga. The soil temperature was measured at a constant depth (several centimetres) along profiles which cover most part of the area of the hot springs. The map shows a high temperature anomaly striking in SE-NW direction. The anomaly passes the area where the hottest spring is located and the new group of hot springs opened after the earthquake from 6th February 1994.

A detailed summary of results of previous geoscientific investigations can be found in Árnason (1994) and Árnason (2003).

Other Studies in the frame of BGR/GSMD project

The geoscientific studies of the joint BGR/GSMD project should achieve the following objectives and answer the following questions:

- clarify the origin of the thermal water of the Buranga hot springs,
- validate or disproof of the existence of a magmatic heat source and in the first case its localization,
- detect of faults/fractures under the sedimentary cover where thermal waters may flow up,
- map the extent of thermal waters in the rift at Buranga prospect and

- localization of active faults in the region around Buranga.

Several ideas for conceptual models of the Buranga geothermal prospect already existed before:
The Buranga hot springs are fed by

• basinal brines ("oilfield brines") of the rift: Sedimentary brines from the Tertiary sedimentary rocks in the rift in depth >2 km below the surface of Buranga with temperatures >125°C stream up along Bwamba fault (overpressure of sedimentary brines, density driven)

• meteoric fluids from high Rwenzori Mountains: Meteoric water flows in open faults down from the higher part of the Rwenzori Massif (3.000-5.000 m asl), and is heated at a depth of 2.000 m below surface (normal geothermal gradient), upstream along Bwamba fault (density driven)

• magmatic fluids of a hidden magma chamber together with meteoric fluids of Rwenzori, i.e. there exists an active magmatic intrusion below Buranga which is the source of heat and gases

The joint BGR/GSMD project started with the aim to validate or disprove the existing conceptual models or to develop a better one. To achieve this, various geoscientific disciplins (structural geology, geochemistry and geophysics) were involved.

A volcanic field is found east of the Rwenzori Massif close to Fort Portal. At Lake Albert indications for magmatic intrusions were deduced from aeromagnetic investigations. In the region of the Albertine Rift, where Buranga is located, no geological surface indications for volcanic activity or intrusive dikes were found so far which could act as a heat source for the thermal water.
However, a first indication of a mantle source for the gas released at Buranga hot springs was found by virtue of the carbon isotopic composition of CO_2. An analyses of He isotopes indicating a contribution of >30% mantle confirmed this result. These findings imply that a still hot, actively degassing magma body exists in the subsurface of Buranga area. The magma body was not yet detected by aeromagnetic surveys perhaps due to its presumed location at or within the Rwenzori basement rocks and because of its weak magnetization due to its still high temperature (Kraml & Kato, 2006).

The geochemical results proofed the existence of a magmatic body in the Buranga area suggesting to identify it as the heat source of the hot springs. This geochemical result motivated us to perform ground geophysical surveys in order to detect and delineate the postulated magmatic intrusion and to recommend locations for geothermal exploration boreholes.

In the beginning of 2005 geophysics started with DC-Soundings, TEM and Gravity (Stadtler & Kraml, 2005). The results of these surveys, however, did not sufficiently delineate a geothermal reservoir for two reasons:

- The bad/impossible accessibility of the terrain avoided to cover adequately the survey area with the measurements. Measurements could only be carried out within a small strip along the Rwenzori Massif.
- Low resistivities in the subsurface almost everywhere did insufficiently allow to distinct between geothermal active and non-active areas.

The known high seismicity at Buranga (about 300 local earthquakes per month) presumably provides excellent requirements to apply seismology. The observation that the activity of the Buranga hot springs is very much related to an active fault system and that these tectonically active faults might provide the migration paths for the hydrothermal water suggested seismology as the appropriate method to be applied in Buranga.

Main trends in seismicity in Rwenzori Area

The main trends in seismicity of the western part of the East African rift system are fairly clear from previous studies, which used teleseismic stations (e.g., DeBremaeker. 1959; Sykes and Landisman, 1964; Wohlenberg, 1969; Fairhead and Girdler, 1971). For better understanding the structure and development of the Rwenzori Mountain region of the East African rift system Maasha (1975) carried out a micro-earthquake survey for a three month period in 1973 using four portable seismographs.
He found that the Rwenzori Region is the most seismically active area in Uganda. In the Rwenzori Region the spatial trends of the micro-earthquakes are correlated with the major rift faults and volcanic zones on the eastern side of the Rwenzori Mountains. The seismicity is shown to extend beneath and transverse to the Rwenzori Mountain block, with hypocentral depths ranged between 0 and 40 km. Elsewhere in the studied region, composite focal mechanism solutions show dip slip motion along steeply dipping planes (Bwamba, Ruimi-Wasa, and Nyamwamba faults). The extensional axes trend east-west. The motion tends to raise the mountain block relative to the surrounding country. A foca1 mechanism determined at the junction of the northern and southern Rwenzori indicates that the northern portion is being uplifted with respect to the southern block.

FEATURES OF THE LOCAL SEISMICITY

Deployment of seismological equipment in Buranga region to record local earthquakes was started in May 2005 with three seismological stations only (Fig. 2: Stations NTAN, KARU, ITOJ).

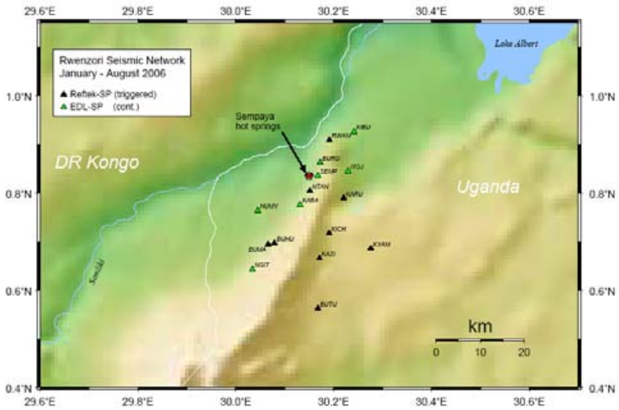

Figure 2. *Map showing the distribution of stations. Note, when project started in April 2005 only 3 sites had been occupied. By and by the number was increased to 15 stations.*

These three stations were operated from May to December 2005 and revealed the very high seismicity (more than 300 local earthquakes per month) of that area, demonstrating that Buranga provides excellent pre-conditions to apply seismology. Therefore it was decided to deploy more stations: 9 stations were operated since January 2006, 15 stations since April 2006. Recording period was finished end of August, 2006. Until April 2006 only Reftek equipment was available for the project which was operated in triggered mode; after this 7 more Earth Data Logger (EDL) were deployed which operated in continuous mode. Short period 1 Hz seismometers of type Mark L-4 3D were used at every station. (The seismological equipment was kindly provided by GFZ Potsdam)

Localization of the events began in 2005 with manually picking of P- and S-phases and is still going on (no automatic picking). This means that only parts of the available data were used for the analysis and interpretation presented in this paper.

Fig. 3 shows the location of earthquakes that have been recorded in March 2006. The active stations are marked as black triangles. The majority of events had a focal depth between 10 and 30 km; some exhibited less and few greater depths. Interestingly, no earthquakes are located within the northern part of the Rwenzori block; all of the events are outside of the marginal faults (Bwamba (west) and Ruimi-Wasa (east) faults (indicated as black solid lines in Fig. 3).

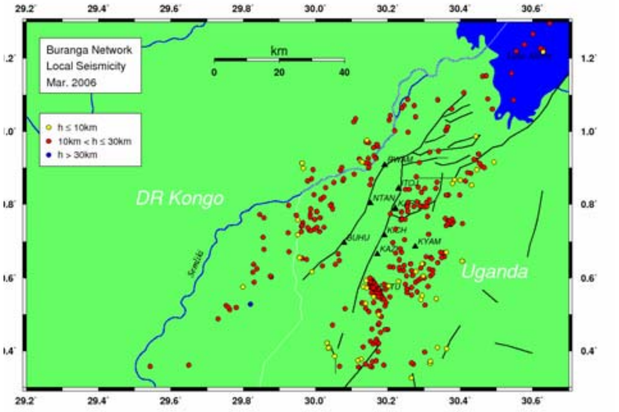

Figure 3. *Location of local earthquakes in March 2006. Operating stations are marked as triangles. Different colors of epicenters indicate different focal depths.*

A very similar distribution of epicenters found for the previous month February 2006 is shown in the upper left part of Figure 4. The upper right and lower left sections present vertical sections of the focal depths. These sections reveal the principal focal depths from 10 to 30 km mentioned before.

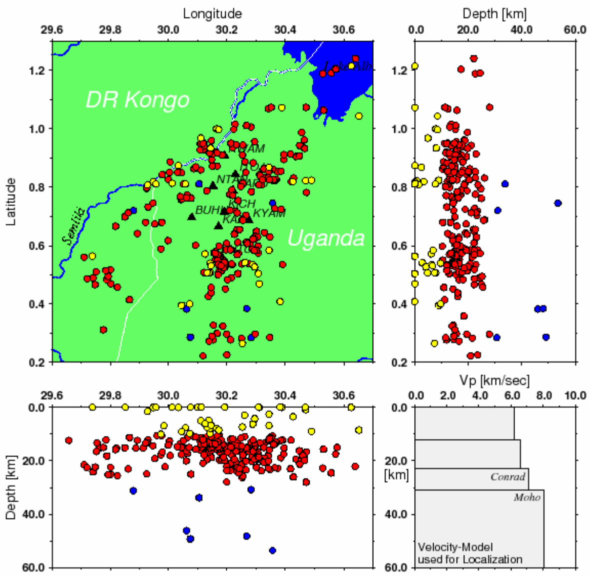

Figure 4. *The distribution of local earthquakes in Feb. 2006 is shown in upper left map. The vertical sections (upper right and lower left) present a projection of focal depths.*

Different from other volcanic mountains associated with the East African rift system, the Rwenzori Mountain is composed of Precambrian rocks (gneisses). Therefore a velocity model with relatively high values (6 km/s) close to the surface was used for locating the hypocenters (lower right in Figure 4). It should be noted here, that our inversion technique applied is supposed to yield much better localizations of the seismic events as well as a more realistic velocity model (see section 4).

The temporal distribution of the seismic activity for the time span considered is given in Figure 5.
Within this period of two months a total number of 760 local earthquakes had been recorded which gives an average activity of 13 events per day. But from the histogram it can easily be seen, that the activity rate is not more or less constant. There are days without any event as well as a day (24th March) with 55 earthquakes. Interestingly these many events are clustered in time and space. These earthquakes are located close to the station BUTU (Fig. 3 and 4) and occurred in a swarm-like activity. This behaviour was observed there not only once but all over our recording period. Moreover this area abounded with the strongest events in that period (two M=4.8 events). These aspects may be used to discuss the possible nature and origin of the seismic activity with respect to their tectonic or magmatic origin (Maasha, 1975).

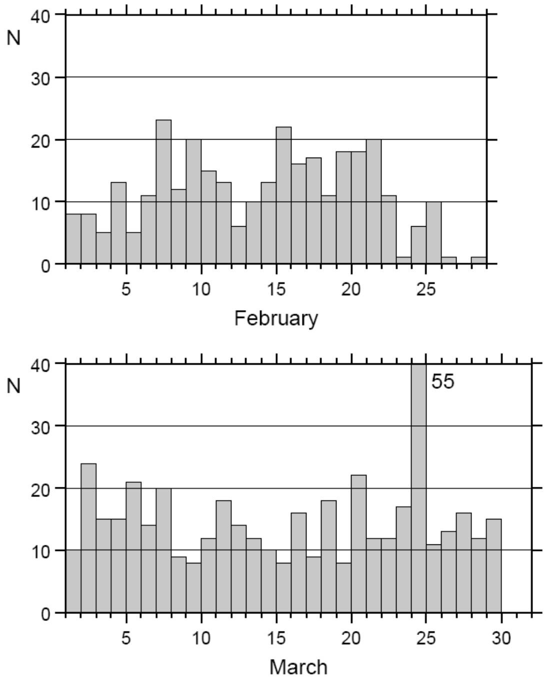

Figure 5. Chronological histograms of 760 located earthquakes in February and March 2006. Average activity is 13 events per day, but the activity is often clustered in space and time and earthquakes occur as swarm.

This is true for the latter events but the majority of earthquakes are believed to be of tectonic origin because of their spacial distribution and their waveforms. A classification can be done using a frequency magnitude relation (e.g. Mogi, 1967) when all data will be analysed.

It is a common observation by the residents of this district that the greatest numbers of earthquake are felt during the rainy season (Maasha, 1975). Our data from northern Rwenzori can support this observation of seasonal variations in seismicity.

IVERSION OF TRAVEL TIME DATA

The micro-earthquake activity around Rwenzori was observed in order to provide information whether an assumed magmatic intrusion could be detected. Sketch:

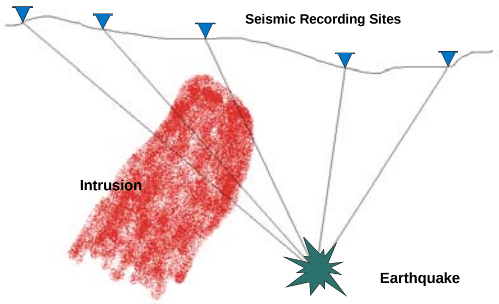

Figure 6. Seismic rays traveling from an earthquake source to recording sites at the surface can exhibit early or late arrival times depending on the velocity anomalies they have passed.

Let us assume a homogeneous crust in which an earthquake happens. Some of the waves that travel to the recording sites at the surface traverse a magmatic intrusion. Furthermore, we assume that the velocity of this intrusion body differs from that of the homogeneous crust. If we correct the travel time for the distance covered, the rays that passed the anomaly will arrive the sites later or earlier, depending on the body's velocity. The early or late arrivals are usually called travel time residuals. These travel time residuals are used to calculate the involved velocity perturbations.

The target of the procedure is to minimize travel time residuals of P- and S-waves at the recording sites. The final solution is achieved using an iterative procedure for earthquake relocation and simultaneous determination of the velocity structure.

A tomographic inversion of travel time data was conducted in order to determine the three-dimensional structure of the P-and S-wave velocity of the crust beneath the network of stations. The tomographic method used for inverting P-wave travel times of teleseismic events was originally developed by Aki et al. (1977). Later this method was extended on local earthquakes and a major improvement of the original method was achieved with including S-waves into that inversion method. We employed a version of that inversion method modified by Koulakov (2002).

Velocity contrast

The velocity contrast between the Precambrian crust and an assumed magmatic intrusion is difficult to estimate because many parameters (ascension temperature, age, pressure, volume…) are unknown. After Kern (1978) and Landolt-Börnstein (1982) a rough mean velocity attenuation of 100m/s per 100°C may be appraised.

Results of the inversion method so far

The outcome of the inversion has to be considered as preliminary because only 30 - 40% of the existing data are included by now. It is not believed that the results will change basically after having included all the existing data, however, some details may be modified. The data subset used for the inversion is presented in Figure 7. The sections do not show the first localizations of the hypocenters but the relocation results. One obvious effect of the relocation is the stronger clustering of events as can be observed around station BUTU or northeast of Station KYAM. This effect will be elaborated in detail together with new results from structural geology.

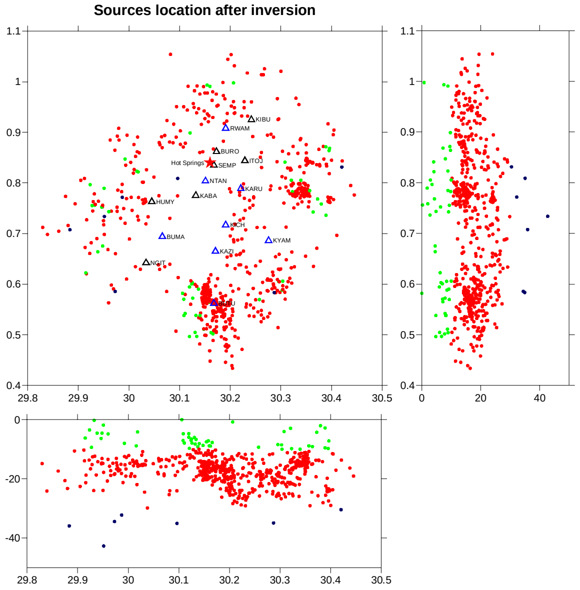

Figure 7. A data subset of 650 events was used for this inversion meaning a total number of ca. 7000 P- and S-rays passed the investigated area. Note that the map does not show the initial locations but the hypocenters after inversion.

To receive an impression on how dense the coverage with rays in our area investigated is the epicenters and receivers have been connected with a line in Figure 8. This Figure shows the P-ray coverage; a picture for S-rays is very similar.

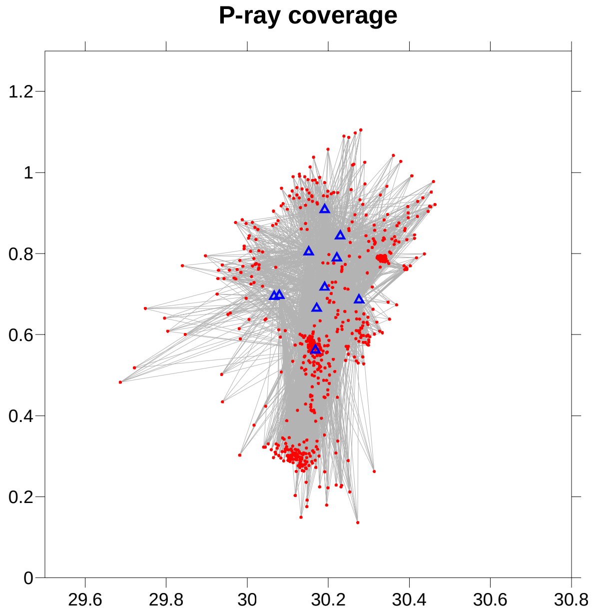

Figure 8. This picture illustrates the coverage of P-rays in the investigated area. For the inversion a similar coverage with S-waves is given.

The applied tomographic inversion method yields velocity model perturbations and refined earthquake locations as well. The velocity anomalies may be presented in horizontal and vertical sections as exemplarily demonstrated in Figure 9 and 10. Please note that the area in Figure 9 is smaller than the area in Figure 8. The reason is that the marginal areas in Figure 8 are not covered with rays as densely as the inner parts and they are therefore less reliable.

This also applies to the vertical section in Figure 10; consequentially the results for depths greater 20 km must be considered as not reliable. The position of the vertical section in this Figure is more or less equal to the direction of the Bwamba fault which is the western margin of the Rwenzori Mountain in Figure 3. The locality of the hot springs is marked with the red star/arrow.

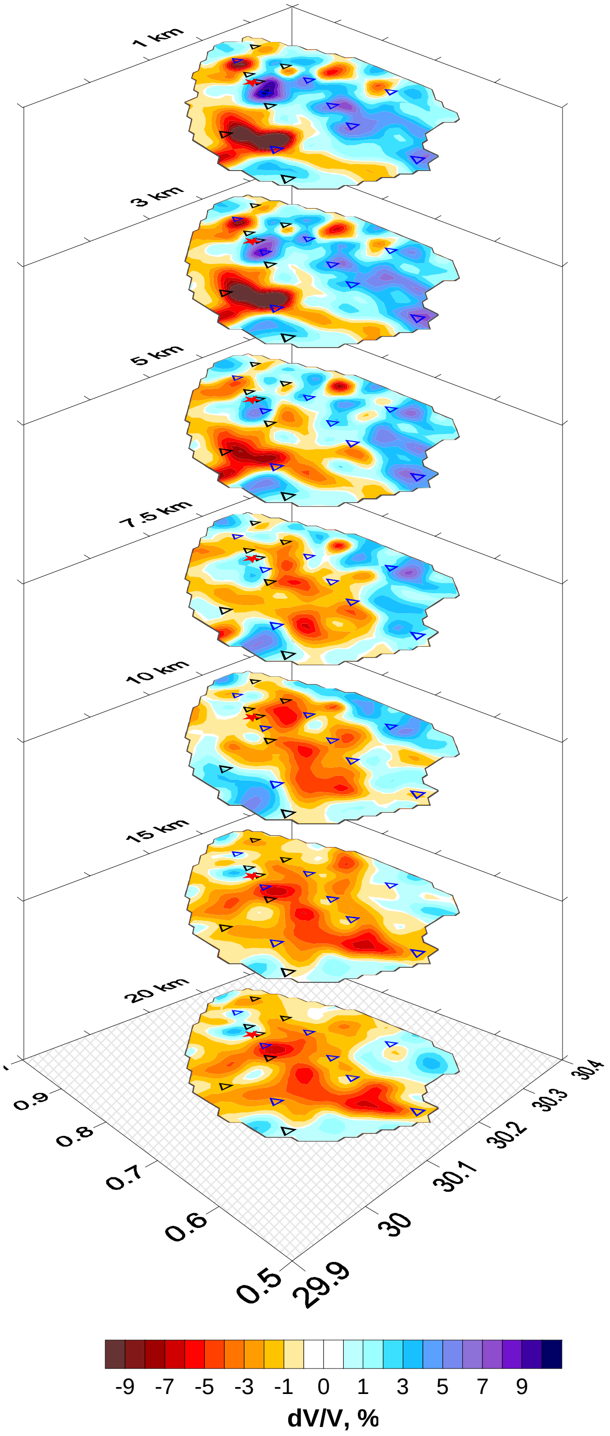

Figure 9. The anomalies of P- and S-velocities may be presented in horizontal sections in different depth levels (here only for P). The assumed "hot" magmatic intrusion should figure out as negative velocity anomaly.

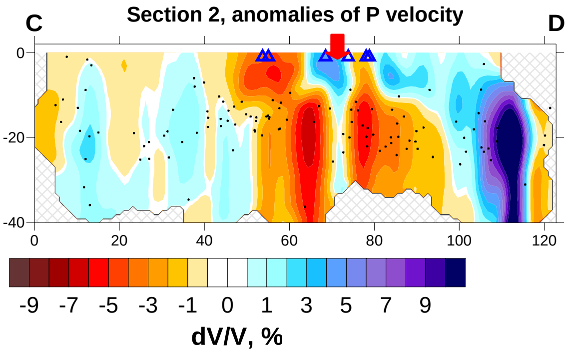

Figure 10. The anomalies of P- and S-velocities may also be presented in vertical sections (here only for P). This section follows the direction of Bwamba fault (western Rwenzori margin). The position of the hot springs is marked with arrow, C belongs to southern direction, D is northeast.

DISCUSSION

As mentioned above the results presented in this paper are preliminary; therefore a detailed discussion cannot follow. The tomography of the seismic data is expected to yield results concerning the exact localization of the hypocenters. This is expected to help in delineating the active faults/fault systems in conjunction with findings from structural geology and will follow later.

Results concerning an underground magmatic intrusion might be summarized as follows (Figure 9): The pattern and characteristics of the low velocity anomalies are in accordance with an interpretation as a hot intrusive body. The size of the anomalies is in the same order as the intrusive bodies which were found in the subsurface of Lake Albert and were deduced from aeromagnetic measurements. Low velocity anomalies are visible at all depths levels. They are relatively strong at shallow depth (1-5 km) and are arranged close to the Bwamba fault, the margin of the Rwenzori Mountains, but outside of the Rwenzori block. Their position does not coincide with the hot springs; they are not directly beneath them. Two unconnected low velocity anomalies are clearly visible north and south of the springs; the southern anomaly seems to have a bigger size.

At greater depth low velocity anomalies are still observable but their position was dislocated towards the centre of the Rwenzori block (Rwenzori root). The anomalies are not as strong as at shallower level.

The given statements also hold for the vertical section in Figure 10.

Details concerning a delineation of the intrusion body can not be given at this state. In order to come to more reliable and detailed inversion result a lot of additional testing is needed and certainly the inclusion of the lacking data. Key words concerning additional testing are: modification of cell size, check board test, affect of random noise, odd/even test, etc. But we believe that our findings until now will be reinforced and better elaborated when all the seismological and particularly the structural geology data will be included.

REFERENCES

AKI, K. Christofferson, A. & Huseby, E.S. 1977: Determination of the Three-Dimensional Structure of the Lithosphere. – J. Geophys. Res., 82, p. 277-296.

ÁRMANNSSON, H. 1994. Geochemical Studies on Three Geothermal Areas in West and Southwest Uganda. Final report. Geothermal Exploration UGA/92/002, UNDEST/GSMD Report

ÁRNASON, K. 1994. Recommendations for geophysical Studies on Three Geothermal Areas in West and South-West Uganda. Report under the project Geothermal Exploration UGA/92/002, UNDEST/GSMD Report

ÁRNASON, K. 2003. Geothermal exploration in the Buranga geothermal field in West Uganda. Island Geosurvey, ISOR, Report

BAHATI, G., PANG, Z., ARMANNSSON, H. ISABIRYE, E. & KATO, V. 2005. Hydrology and reservoir characteristics of three geothermal systems in western Uganda. Geothermics, 34, 568–591

DEBREMAEKER, J., 1959: Seismicity of the West African rift valley, J. Geophys. Res.. 64, 1961-1966.
FAIRHEAD, J. D., and R. W. GIRDLER, 1971:The seismicity of Africa, Geophys. J. Roy. Astron. Soc.. 24. 271.

GÍSLASON, G., NGOBI, G., ISABIRYE, E. & TUMWEBAZE, S. 1994. An Inventory of Three Geothermal Areas in West and Southwest Uganda. Geothermal Exploration UGA/92/002, UNDEST/ GSMD, a draft report

IAEA 2003. Isotope hydrology for exploring geothermal resources. IAEA TC-Project, UGA/8/003, Terminal Report

KRAML, M. & KATO, V. 2006: personal communication

KERN, H. 1978: The effect of high temperature and high confining pressure on compressional wave velocities in Quartz-bearing and Quartz-free igneous and metamorphic rocks. –Tectonophysics, 44, p. 185-203.

LANDOLT-BÖRNSTEIN, 1982: Zahlenwerte und Funktionen aus Naturwissenschaft und Technik. – Springer Verlag

MAASHA, N. 1975. The Seismicity of the Rwenzori Region in Uganda. Journal of Geophysical Research, 80, No. 11, p. 1485 - 1496

MAASHA, N. 1975. Electrical resistivity and microearthquake surveys of the Sempaya, Lake Kitagata, and Kitagata geothermal anomalies, Western Uganda. Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, 20.-29. May 1975, p. 1103-1112

MCCONNEL, R.B. & BROWN, J.N. 1954. Drilling for geothermal power at Buranga Hot Springs, Toro. First Progress Report. Geological Survey of Uganda, Unpub. Report No. JMB/17 (RBM/16)

MOGI, K. 1967. Earthquakes and fractures. Tectonopysics, 5, p. 35 – 55

OCHMANN, N., HOLLNACK, D. & WOHLENBERG, J. 1989. Seismological Exploration of the Milos Geothermal Reservoir, Greece. Geothermics, 18, 4, p. 563 – 567

PALLISTER, J. W., 1971: The tectonics of East Africa, Tectonics Afr. Unesco Earth Sci., 6, 511-542.

STADTLER, C. & KRAML, M. 2005. GEOTHERM Project in Uganda - Geophysical and geochemical investigations at the Buranga hot springs, Albertine Rift, Uganda – Interim Report. Hannover, BGR, 0125802

SYKES, L. R., LANDISMAN, M., 1964: The seismicity of East Africa, the Gulf of Aden and the Arabian and Red seas, Bull. Seismol. Soc. Amer., 54. 1927-1940

WOHLENBERG, J., 1969: Remarks on the seismicity of East Africa between 4°N-12°S and 23°E-40°E, Tectonophysics, 8, 567-577.