

MICROEARTHQUAKE SURVEY AT THE BURANGA GEOTHERMAL PROSPECT, WESTERN UGANDA

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ABSTRACT

The BGR supports the Government of Uganda in the geoscientific investigations at 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 most likely 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 requirements 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 underground magmatic intrusion and
- via an exact localization of the hypocenters delineation of the active faults/fault systems.

The first results, which will be reinforced and better elaborated when all the data will be included, are presented in this paper. Low velocity anomalies, which most likely represent the magmatic intrusion body, are shown in horizontal and vertical sections and are constituted in 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 to the Semliki River, which is the borderline to the Democratic Republic of

Congo. The springs are situated in a swamp in the 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 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 that is still flowing; in February 2005 the measured water temperature was 62°C.

In 1973 two Schlumberger soundings were measured at Buranga. The soundings 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 (Ármanncsson, 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 constant depth (several centimeters) on profiles which cover most part of the area of the hot springs. The map shows a high temperature anomaly that strikes 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).

Studies in line with BGR/GSMD project

The geoscientific studies of the joint BGR/GSMD project were aimed at achieving and solving the following objectives and questions which shall be achieved and solved by the geoscientific investigations: clarification of the origin of the thermal water of the Buranga hot springs, validation or disproof of the existence of a magmatic heat source and in the first case its localization, detection of faults/fractures under the sedimentary cover where thermal waters may flow up, mapping 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 existed:

- Buranga is 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 $>125^{\circ}\text{C}$ stream up along Bwamba fault (overpressure of sedimentary brines, density driven)

- Buranga is fed by 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 in a depth of 2.000 m below surface (normal geothermal gradient), upstream along Bwamba fault (density driven)

- Buranga is fed by magmatic fluids of a hidden magma chamber together with meteoric fluids of Rwenzori: Active magmatic intrusion below Buranga which is also 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, a cooperation of various geoscientific departments (structural geology, geochemistry and geophysics) commenced.

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, from carbon isotopic composition of CO_2 a first indication of a mantle source for the gas released at Buranga hot springs was found. This was confirmed by He isotopic analyses indicating a contribution of $>30\%$ mantle He. These findings imply that a still hot actively degassing magma body exists in the subsurface of Buranga area. The magma body was so far not detected by aeromagnetic surveys perhaps due to its presumed location at or within the Rwenzori basement rocks and its still hot temperature (Kraml & Kato, 2006).

The fact that geochemical results proofed the existence of a magmatic body in Buranga area suggests itself to serve as the heat source of the hot springs. This finding defined the task of active ground geophysics in detecting and delineating the magmatic intrusion and recommending locations for geothermal exploration boreholes.

In the beginning of 2005 geophysics started a first attempt with DC-Soundings, TEM and Gravity (Stadler & Kraml, 2005). These methods were carried out as far as possible, but results of this survey were insufficient to delineate a geothermal reservoir for two reasons:

- The bad/impossible accessibility of the terrain avoided to cover adequately the

survey area with the measurements necessary for identifying a potential geothermal reservoir. Measurements could only be carried out in a small strip along the Rwenzori Massif.

- Low resistivities in the subsurface were detected almost everywhere leading to insufficient distinction of results between geothermal active and non-active areas.

The known high seismicity (about 300 local earthquakes per month) suggested that Buranga 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 microearthquake survey for a three month period in 1973 with 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 microearthquakes 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 focal 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).

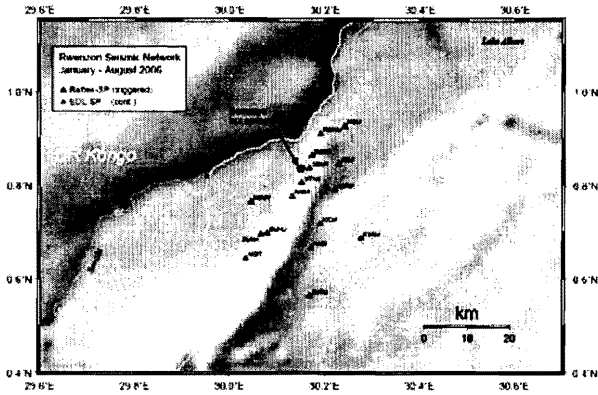


Figure 2. Map showing the distribution of stations. Note, when project started in April 2005 only 3 sites had been occupied. By and by the number was increased to 15 stations.

These three stations were operated from May to December 2005 and emerged the very high seismicity (more than 300 local earthquakes per month) of that area, demonstrating that Buranga provides excellent requirements 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 begun 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 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. Interesting is that within the northern part of the Rwenzori block no earthquakes were located; 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).

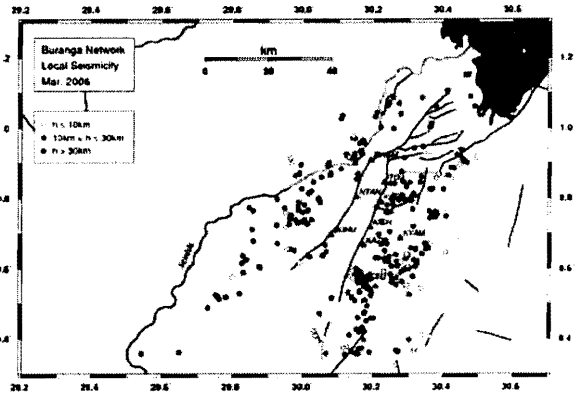


Figure 3. Location of local earthquakes in March 2006. Operating stations are marked as triangles. Different colors of epicenters indicate different focal depths.

A very similar distribution of epicenters is found for the previous month February 2006 which 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 before mentioned principal focal depths from 10 to 30 km.

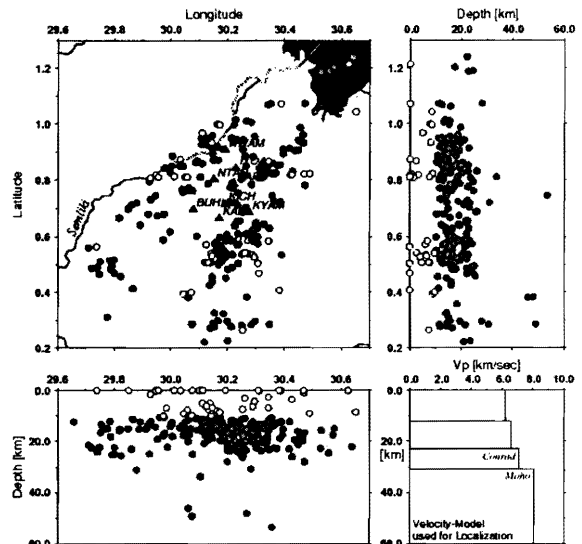


Figure 4. The distribution of local earthquakes in Feb. 2006 is shown in upper left map. The vertical sections (upper right and lower left) present a projection of focal depths.

In contrast to other mountains associated with the East African rift system, which are of volcanic origin, 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 is noted here, that a highly improved localization of the seismic events as well as the velocity model will come along with the applied inversion technique (see section 4).

The temporal distribution of the seismic activity for the considered time span is given in Figure 5. Within this period of two months a total number of 760 local earthquakes had been located which gives an average activity of 13 events per day. But from the histogram it can easily be read, that the activity is not connected with a more or less constant rate. 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 behavior 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 seismic activity with respect to tectonic or magmatic origin (Maasha, 1975).

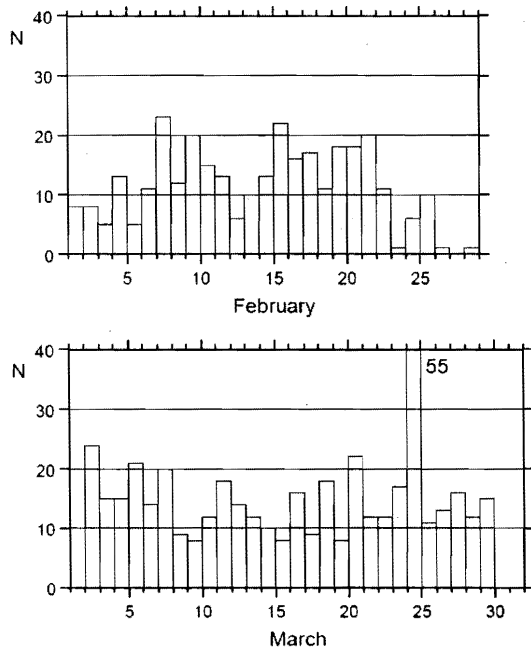


Figure 5. Chronological histograms of 760 located earthquakes in February and March 2006. Average activity is 13 events per day, but the activity is often clustered in space and time and earthquakes occur as swarm.

This is true for the latter events but the majority of earthquakes is believed to be of tectonic origin when

looking at there special distribution and there waveforms. A classification can be done using a frequency magnitude relation (e.g. Mogi, 1967) when all data is analyzed.

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

INVERSION OF TRAVEL TIME DATA

In general, the microearthquake activity around Rwenzori was observed to provide information on the question whether an assumed magmatic intrusion could be detected with this approach or not. The conception might be explained with the following sketch:

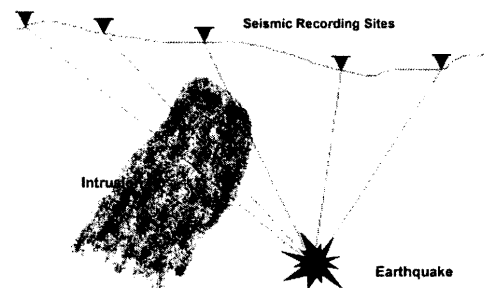


Figure 6. Seismic rays traveling from an earthquake source to recording sites at the surface can exhibit early or late arrival times depending on the velocity anomalies they have passed.

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. Let us also assume that this intrusion body has a different velocity from the homogeneous crust. If we correct the travel time for the distance covered, the rays that passed the anomaly will arrive the sites late or early depending on the body's velocity being low or high. 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 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 to invert 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 that was modified by Koulakov (2002).

Velocity contrast

The velocity contrast between the Precambrian crust and an assumed magmatic intrusion is hard 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 this inversion method which is presented in this paper is preliminary because only 30 - 40% of the existing data is included by now. It is not believed that the results will change basically when all the existing data will be included, but some details may be modified. The data subset that was

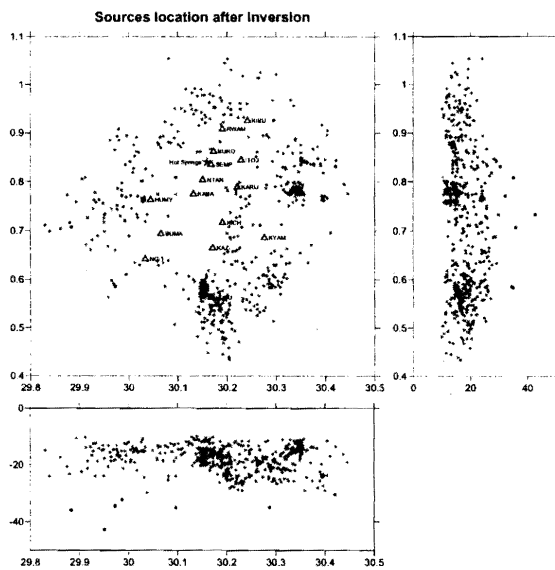


Figure 7. A data subset of 650 events was used for this inversion meaning a total number of ca. 7000 P- and S-rays passed the investigated area. Note that the map does not show the initial locations but the hypocenters after inversion.

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.

To receive an impression on how dense the coverage with rays in our investigation area 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.

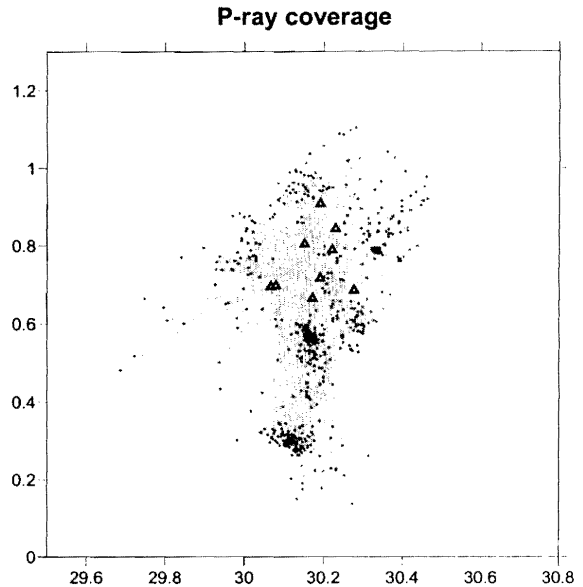


Figure 8. This picture illustrates the coverage of P-rays in the investigated area. For the inversion a similar coverage with S-waves is given.

The findings of the applied tomographic inversion method are velocity model perturbations as well as refined earthquake locations. 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. That is because the marginal areas in Figure 8 are not as densely covered with rays as the inner parts and therefore considered less reliable.

This conclusion 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.

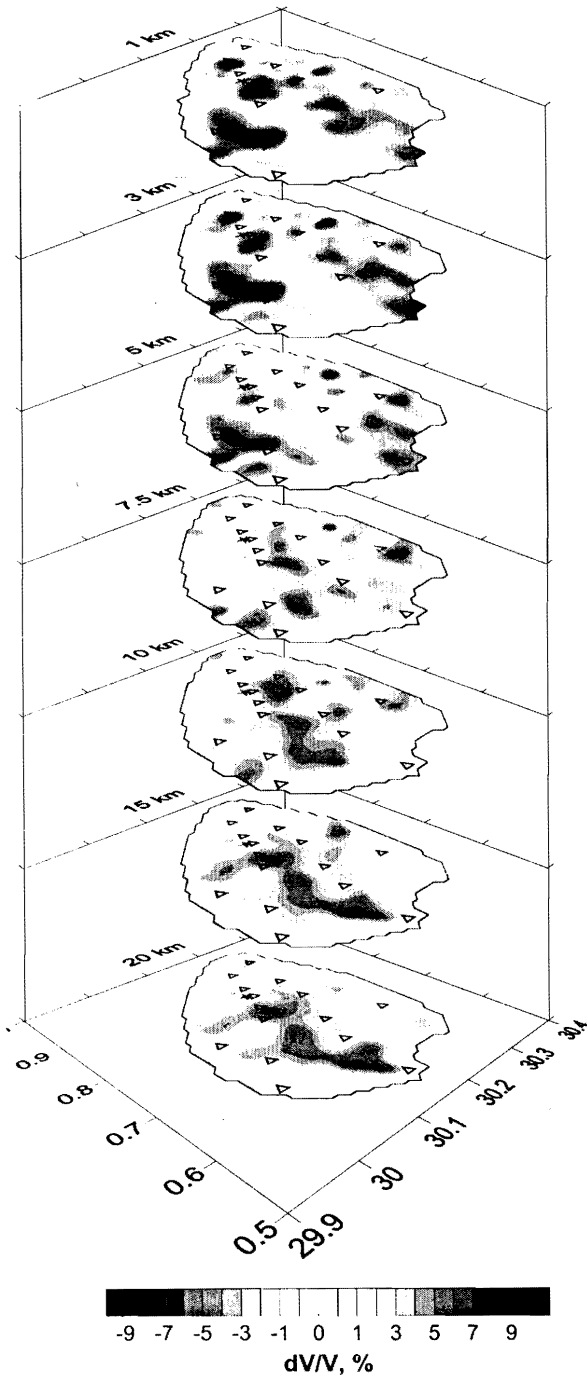


Figure 9. The anomalies of P- and S-velocities may be presented in horizontal sections in different depth levels (here only for P). The assumed "hot" magmatic intrusion should figure out as negative velocity anomaly.

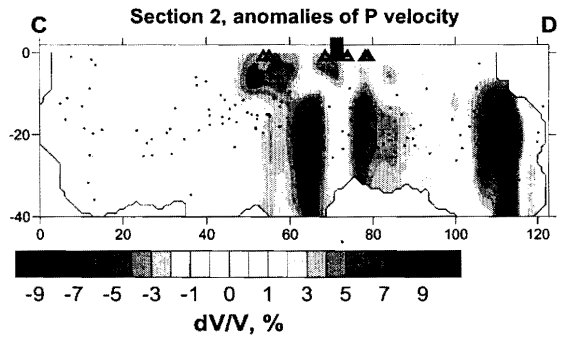


Figure 10. The anomalies of P- and S-velocities may also be presented in vertical sections (here only for P). This section follows the direction of Bwamba fault (western Rwenzori margin). The position of the hot springs is marked with arrow, C belongs to southern direction, D is northeast.

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 delineation of 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 in 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.

In greater depth low velocity anomalies are still constitutable 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. 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, application of random noise, odd/even test, etc. But it is believed that the above made statements will be reinforced and better elaborated when all the seismological as well as particularly the structural geology data will be included.

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