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GEOHAZARDS IN GEOTHERMAL EXPLOITATION

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ABSTRACT

Geohazards need to be taken into account in harnessing of geothermal areas. This applies in particular to the high temperature type which is in one way or another related to volcanic or intrusive centres. The issues to be regarded include the type and history of volcanism, definition of segments with most active fault movements, earthquake activity including microseismicity, slope stability and possibility of flash floods. Gas fluxes from magma chambers or intrusive activity may cause corrosion problems of production wells. In geothermal systems of restricted recharge drawdown of the reservoir fluid causes thickening of the overlying steam zone and increased surface geothermal activity.

Hazards involved with exploitation of low and high temperature geothermal systems where hosted in sedimentary or thick pyroclastic deposits having limited recharge may cause ground subsidence and damage to buildings and roads.

1. INTRODUCTION

Geohazards in high temperature geothermal fields involve earthquakes, volcanic eruptions, fault movements, intrusions, gas fluxes emanating from intrusive bodies, and rock slides. Earthquakes and intrusions are not only hazardous; they may also prove beneficial for the geothermal systems by maintaining/stimulating secondary permeability. Magma movement is not always associated with volcanic eruptions. Monitoring of ground movements associated with production from the reservoir and latent creep or rifting episodes in extensional geological settings will be touched upon briefly.

For assessment of geohazards in the East African Rift it is necessary to collect information about former events. Reliable documentation of events there reaches back only about one and a half century as regards earthquakes and volcanic eruptions. As regards the latter, prehistoric eruptions can often be dated and also defined as to type (explosive or effusive) and volumes. The past is here the key to the present.

2. LARGE TECTONIC EARTHQUAKES

Large tectonic earthquakes are the most hazardous. Figure 1 shows earthquakes which occurred in East Africa in the period 1963-1989 (Kaban and Kuhanek, 1991). The epicentres including aftershocks may define active faults underground. There have been 20 quakes of magnitude (M 6.5 to 7.4) in East Africa since 1970, all of them in the Western Rift. The depth of most is between 10 to 33 km (NEIC catalogue) (Figure 2). Large earthquakes occur also in the Eastern Rift, but they are rare. The largest occurred in 1908 in Ethiopia. Earthquake swarms with hundreds of shocks occur (largest of M 4-5.5) but they do

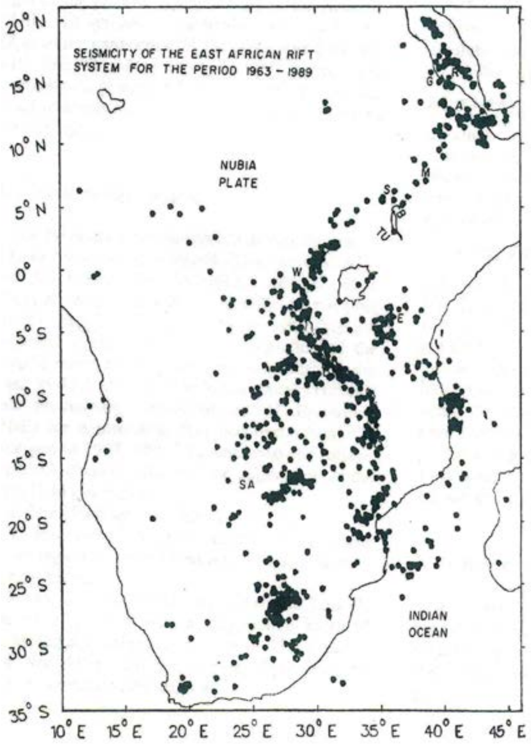

FIGURE 1: Seismicity of the East African Rift system and southern Red Sea for the period 1963-1989. Solid circles denote earthquake epicentres taken from National Oceanic and Atmospheric Administration (NOAA) catalogue. (From: Kbede and Kulhánek, 1991)

NEIC: Earthquake Search Results

U. S. GEOLOGICAL SURVEY

EARTHQUAKE DATA BASE

CAT	YEAR	MO	DA	ORIG TIME	LAT	LONG	DEP	MAGNITUDE
PDE	1973	08	28	150159.10	-0.19	-18.03	33	6.9 UKPAS
PDE	1975	10	07	082809.50	0.90	-26.77	33	6.7 MsGS
PDE	1979	08	25	084404	10.73	-41.69	10	6.6 MsGS
PDE	1982	01	03	140950.45	-0.97	-21.87	10	6.5 MsGS
PDE	1984	11	01	044850.27	8.19	-38.79	10	7.4 MSBRK
PDE	1985	06	06	024012.95	0.93	-28.43	10	6.6 MSBRK
PDE	1992	08	28	181846.44	-0.96	-13.56	15	6.9 MwGS
PDE	1992	12	26	195224.90	-0.56	-19.32	27	6.8 MwHRV
PDE	1994	03	14	043015.75	-1.28	-23.57	10	7.0 MwGS
PDE	1995	05	18	000627.46	-0.89	-22.00	12	6.8 MwHRV
PDE	1996	02	16	094458.41	-1.50	-15.28	10	6.6 MwHRV
PDE	1996	02	18	234928.16	-1.27	-14.27	10	6.6 MwHRV
PDE	1996	06	02	025209.55	10.80	-42.25	10	7.0 MwHRV
PDE	1996	12	10	083618.70	0.87	-30.04	10	6.7 MwHRV
PDE	2003	11	09	195236.82	-0.67	-19.69	10	6.6 MwHRV
PDE	2003	12	21	074045.83	-0.77	-20.60	10	6.6 MwHRV
PDE	2005	01	12	084003.65	-0.88	-21.19	10	6.8 MwGS
PDE	2007	08	20	224228.53	8.04	-39.25	6	6.5 MwGCMT
PDE	2008	02	08	093814.10	10.67	-41.90	9	6.9 MwUCMT
PDE-W	2008	04	24	121449.92	-1.18	-23.47	10	6.5 MwUCMT
PDE-W	2008	05	23	193534.94	7.31	-34.90	9	6.5 MwUCMT

FIGURE 2: Earthquakes of M 6.5 and larger in East Africa since 1970 (From: USGS)

not cause much damage normally. They may define also some specific features such as intrusions or fracturing due to cooling in the periphery of existing shallow magma chambers.

3. VOLCANIC ERUPTIONS

Volcanic eruptions in the Rift system are different as regards area and type. Basaltic fissure eruptions occur on elongate volcanic systems in the north, as in Djibouti (Ardoukoba 1978) and in Ethiopia (Dabbahu 2005-2008) (Figure 3). The Dabbahu episode may still be going on with repeated dyke injections from the magma chamber underneath Dabbahu into the fissure swarm. There have been 15 dyke injections so far including three fissure eruptions. In the south of the rift silicic rocks are more common, being erupted either as thick flows or domes restricted in area and volume, or as pyroclastic flows and surges. Air fall ash and pumice usually accompany the silicic eruptions, forming quite thick deposits in the vicinity of the eruption site, but dispersed far by winds. The only documented big explosive volcanic eruption in the Rift occurred in Eritrea (Dubbi) in 1861. The volcano erupted trachytic pumice and ash flows in the initial phase, followed by basaltic lavas of over 1 km³. Voluminous pyroclastic flows may spread over large

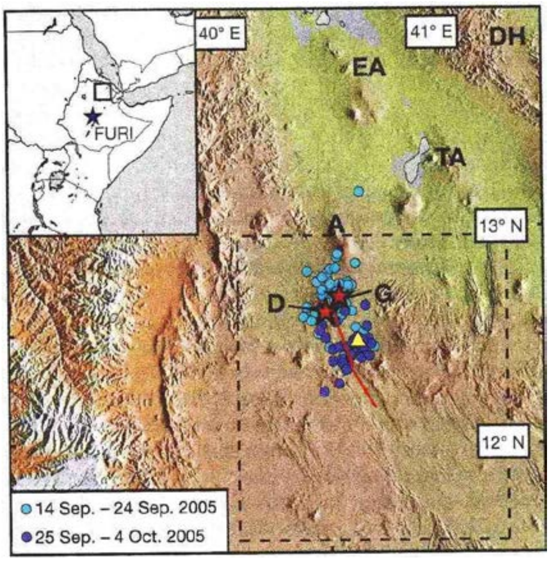

FIGURE 3: Red line shows location of dyke and red stars mark Dabbahu volcano. (From: Wright et al., 2006)

areas and be followed by caldera collapses. Fortunately such events are rare but so far only few volcanoes have been investigated about their past paroxysmal eruptions.

In Kenya the histories of at least three major centres have been investigated in some detail: Menengai (Leat, 1984), Longonot (Scott, 1980), last eruption in 1863, and Suswa, but also Olkaria (Naylor 1972) (last eruption in 1770 according to Smithsonian). Figures 4-7 list the volcanoes of the Eastern Rift and when they were last active. Flows and surges may alternate in one and the same eruption. Surges do not spread as far as flows, little over 6 km from the source as a rule. Menengai and Longonot had their mega-eruptions and caldera collapses 10-30,000 years ago. Post caldera activity has been restricted to the calderas and their fissure swarms down the north and south flanks.

Name	Elevation		Location	Last eruption
	meters	feet	Coordinates	
The Barrier	1032	3385	2.32, 36.57	1921
Central Island	550	1804	3.5, 36.042	-
Chyulu Hills	2188	7178	-2.68, 37.88	1855
Mount Elgon	4321	14178	-1.1, 34.5	
Elmenteita Badlands	2126	6975	-0.52, 36.27	Holocene
Emuruangogolak	1328	4357	1.5, 36.33	1910
Homa Mountain	1751	5745	-0.38, 34.5	Holocene
Mount Kenya	5199	17057	0°9'S 37°18'E	-
Korosi	1446	4744	0.77, 36.12	Holocene
Likaiu	915	3000	2.17, 36.36	-
Longonot	2776	9108	-0.914, 36.446	1863
Marsabit	1707	5600	2.32, 37.97	Holocene
Menengai	2278	7472	-0.2, 36.07	6050 BC
Namarunu	817	2680	1.9, 36.27	6550 BC
North Island (Kenya)	520	1706	4.07, 36.05	-
Nyambeni Hills	750	2460	0.23, 37.87	Holocene
Ol Doinyo Eburru	2856	9370	-0.63, 36.23	-
Ol Kokwe	1130	3707	0.63, 36.08	Holocene
Olkaria	2434	7985	-0.904, 36.292	1770
Paka	1697	5568	0.92, 36.18	6050 BC
Segererua Plateau	699	2293	1.57, 37.9	Holocene
Silali	1528	5013	1.15, 36.23	5050 BC
South Island (Kenya)	800	2625	2.63, 36.6	1888
Suswa	2356	7730	-1.175, 36.35	-

FIGURE 4: List of volcanoes in Kenya (From: Wikipedia)

4. FAULT MOVEMENTS

Fault movements may create ground fissures in the epicentral areas of large earthquakes. In the Rift system they would presumably follow the trace of pre-existing normal faults. Earthquakes associated with magmatically driven rifting are not as strong, probably not much over M 5.5. They are associated with dyking. Ruptures associated with tectonic earthquakes would propagate at a rate of kilometres/second as against kilometres/hr for the latter which accompany dyke propagation. The fissures themselves would cause damage of surface structures where they cross pipelines or cut through boreholes. Needless to say that mapping of faults is important at the stage of site selection.

5. INTRUSIONS

Intrusions make themselves felt in two ways. We mentioned above that they may form dykes when magma is expelled laterally out of a magma chambers during rifting events. They may also form sheets in the roof of magma chambers both as irregular net veins or regularly inclined as cone sheets as a result of point source stresses. Dykes have made themselves felt when they cut through and clog boreholes. Examples are known from Krafla where a borehole erupted basalt and several were clogged as became evident from fresh glassy basalt being drilled through when cleaned.

6. GAS FLUXES

The magma chambers themselves have an aureole of magmatic gases such as CO_2, SO_2, Cl and F in a supercritical water phase around them. These may

Name	Elevation		Location	Last eruption
	meters	feet	Coordinates	
Ardoukoba	298	978	11.58, 42.47	1978
Boina	300	984	11.25, 41.83	Pleistocene
Garbes	1000	3281	11.42, 42.2	Pleistocene
Tiho	500	1640	11.53, 42.05	Uncertain

FIGURE 5: List of volcanoes in Djibouti (From: Wikipedia)

Name	Elevation		Location	Last eruption
	meters	feet	Coordinates	
Alid	910	2966	14.88, 39.92	Holocene
Asseb	910	2986	12.85, 42.43	Holocene
Dubbi	987	5331	13.58, 41.808	1861
Gufa	600	1969	12.55, 42.53	Holocene
Jalua	713	2339	15.042, 39.82	*unknown*
Mousa Ali	2028	6654	12.47, 42.4	Holocene
Nabro	2218	7277	13.37, 41.7	*unknown*

FIGURE 6: List of volcanoes in Eritrea (From: Wikipedia)

migrate off during times of unrest and pollute the geothermal system (lowering its pH), rendering it partly unexploitable for years, or even decades. The Krafla geothermal system is an example being situated in the caldera of a degassing volcano. An informative paper on volatile fluxes from volcanoes at rest is given by Brantley et al. 1993.

The sediment filled grabens of the Western Rift contain methane gas, which comes from organic material trapped in the lake. Reserves are well known in Lake Kivu and signs of it have been found elsewhere. Thus the western shore of Lake Tanganyika is leaking hydrocarbons (There is a Tanganyika oil company). Drilling into the rift floor needs to take notice of this.

7. DRILLING INTO MOLTEN ROCK

Shallow depth to molten rock may cause problems. One possibility is a blowout, not known to have occurred for this reason yet. The reality of drilling into a basaltic melt came up fife years ago in Hawaii and in late 2008 at Krafla, Iceland, in both cases at about 2500 depth. At Krafla the yielding wells are located in an area of Late Pleistocene and Recent explosion craters (Figure 8). In our case the drill penetrated 50 m into the molten body (not recognized as such, because there had been a total loss of drill fluid which was water), then got stuck as circulation was stopped for a temperature log (showed 386°C at the bottom of the drill string) (Figure 9). The string was blasted above the hot part. The drill pipe broke well below. On pulling out, the lowest pipe was found to be plugged by fresh, silicic glass. Even though a feed zone just above the now recognized molten zone was plugged with cement, the well yielded low pH fluid which is corrosive. A well which was completed at Krafla end 2007 ran into a gas rich fluid at the same depth (Figure 10) (Thorhallsson et al., 2008). That particular feed zone was cemented off and the well is a moderately good producer. In summer 2009 again a research borehole which was scheduled for 4000 m depth ran into molten rhyolite at 2300 m and had to be abandoned. There was a large feed zone just above the melt. Due to excessive pumping of cold water into it the well is heating up slowly. It is not yet known whether the well will be usable. Figure 11 shows the location of the three wells that ran into molten rock and a gas rich aureole presumed to surround it.

Name	Elevation		Location	Last eruption
	meters	feet	Coordinates	
Adwa	1733	-	10.07, 40.84	1928
Afdera	1295	5686	13.08, 40.85	Holocene
Alayta	1501	4924	12.88, 41.57	1915
Ale Bagu	1031	3883	13.52, 40.63	Holocene
Alu	429	1407	13.82, 40.56	-
Alutu	2335	7661	7.77, 38.78	50 BC
Amoissa	1733	5684	10.069, 40.837	-
Asavyo	1200	3937	13.07, 41.6	Holocene
Asmara (volcano)	500	-	11.27, 41.52	Holocene
Ayalu	2145	7037	10.08, 40.7	1928
Beru	1100	3609	8.95, 39.75	Holocene
Bilate River Field	1700	5577	7.07, 38.1	Holocene
Bishoftu Volcanic Field	1850	6069	8.78, 38.98	Holocene
Bora-Bericcio	2285	7497	8.27, 39.03	Holocene
Borale Ale	668	2192	13.725, 40.6	Holocene
Borawli	875	2871	11.63, 41.45	Holocene
Borawli	812	2664	13.3, 40.98	Holocene
Boset-Bericha	2447	8028	8.558, 39.475	Holocene
Butajiri-Silti Field	2281	7484	8.05, 38.35	-
Chiracha	1650	5413	6.65, 38.12	Holocene
Corbetti Caldera	2320	7611	7.18, 38.43	-
Dabbahu	1442	4731	12.6, 40.48	Holocene
Dabbayra	1302	4272	12.38, 40.07	Holocene
Dalaffilla	613	2011	13.792, 40.55	-
Dallol	-48	-157	14.24, 40.3	1926
Dama Ali	1068	3504	11.28, 41.63	1631
Dendi	3260	10,692	9, 38	-
Dofen	1151	3776	9.35, 40.13	Holocene
East Zway	1889	6097	7.95, 38.93	-
Erta Ale	613	2011	13.6, 40.67	2006
Mount Fentale	2007	6585	8.97, 39.93	1820
Gabillema	1459	4787	11.08, 41.27	Holocene
Gada Ale	287	942	13.975, 40.408	Holocene
Gariboldi Caldera	1619	-	8.8, 39.69	-
Gedamsa Caldera	1984	6509	8.35, 39.18	Holocene
Groppo	930	3051	11.73, 40.25	Holocene
Hayli Gubbi	521	1709	13.5, 40.72	Holocene
Hertali	900	2953	9.78, 40.33	Holocene
Hobicha Caldera	1800	5905	6.78, 37.83	Holocene
Kone	1619	5312	8.8, 39.69	1820
Korath Range	912	2992	5.1, 35.88	Holocene
Kurub	625	2051	11.88, 41.208	Holocene
Liado Hayk	878	2881	9.57, 40.28	Holocene
Ma Alalta	1815	5955	13.02, 40.2	Holocene
Mallahle	1875	6152	13.27, 41.65	Holocene
Manda Hararo	600	1968	12.17, 40.82	Holocene
Manda-Inakir	600	1968	12.38, 42.2	1928
Mat Ala	523	1716	13.1, 41.15	Holocene
Mega Basalt Field	1067	3501	4.08, 37.42	Holocene
O'a Caldera	2075	6808	7.47, 38.58	-
Sabober	-	-	8.97, 39.93	-
Lake Shala	2075	6806	7.47, 38.55	-
Sodore	1765	5791	8.43, 39.35	Holocene
Sork Ale	1611	5285	13.18, 41.725	Holocene
Tat Ali	700	2297	13.28, 41.07	Holocene
Teppi	2728	8950	7.42, 35.43	Holocene
Tosa Sucha	1650	5413	5.92, 37.57	Holocene
Tullu Moje	2349	7707	8.15, 39.13	1900
Wonchi	3450	11,316	9, 38	-
Mount Yangudi	1383	4537	10.58, 41.042	Holocene
Mount Zuqualla	2800	9184	8.32, 38.52	-

FIGURE 7: List of volcanoes in Ethiopia (From: Wikipedia)

8. FLOODING AND SLIDING

Flooding and sliding involves a hazard in areas of steep topography, clayey ground (a common feature in high temperature geothermal fields) and heavy, in particular tropical, rain which may cause flash floods. The selection of drill pads, siting of buildings and layout and construction of steam pipes needs to be considered with regard to such hazard factors.

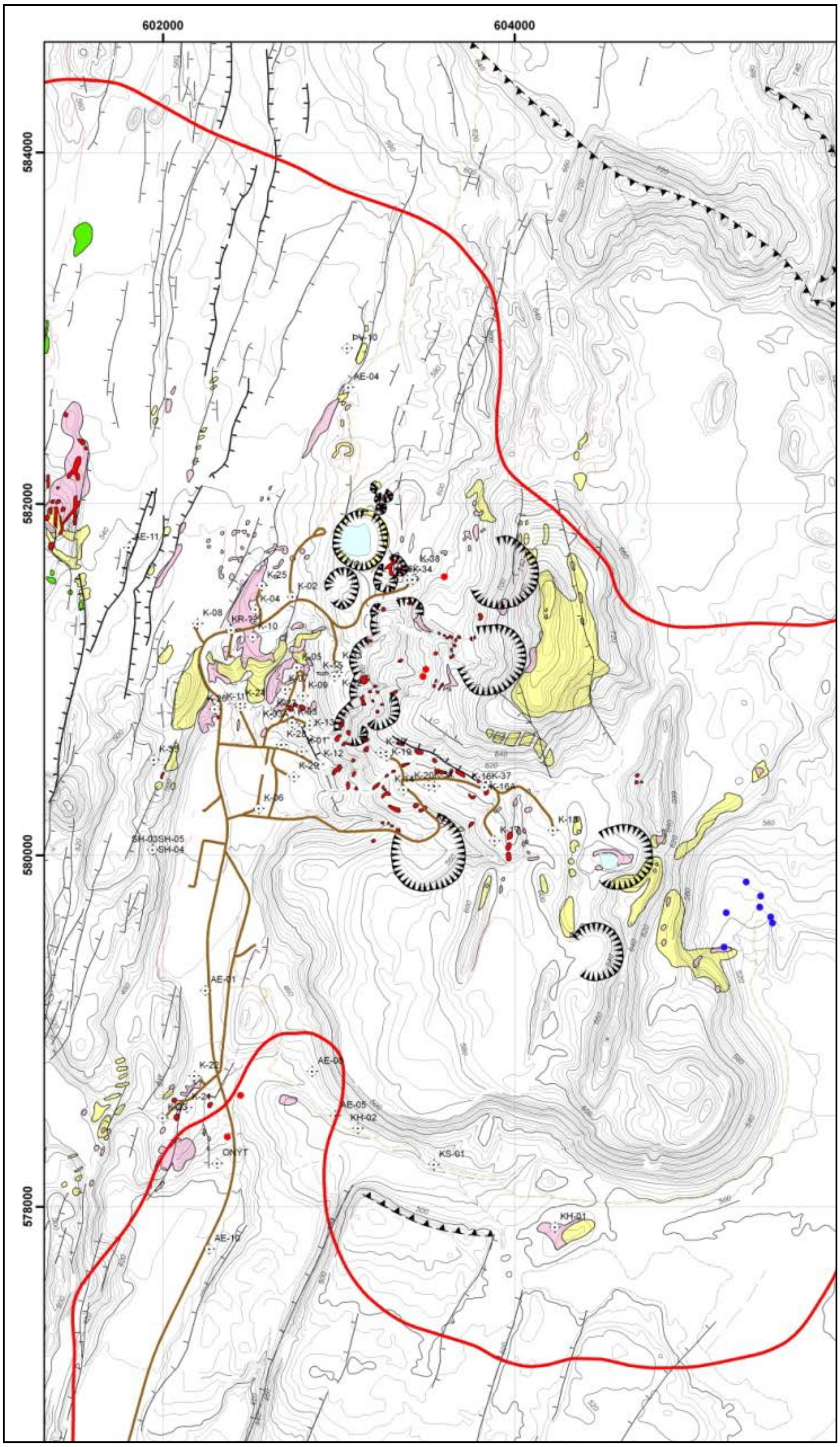

FIGURE 8: Explosion craters (circular) of Krafla geothermal area. Red line marks the outline of a high resistivity body at 600 m depth, enveloped by a low resistivity zone. Red dots are fumaroles. High grade surface alteration is pink. Low grade alteration is yellow. Normal faults are shown. Caldera margin is shown at upper right and lower centre. (From: ISOR database.)

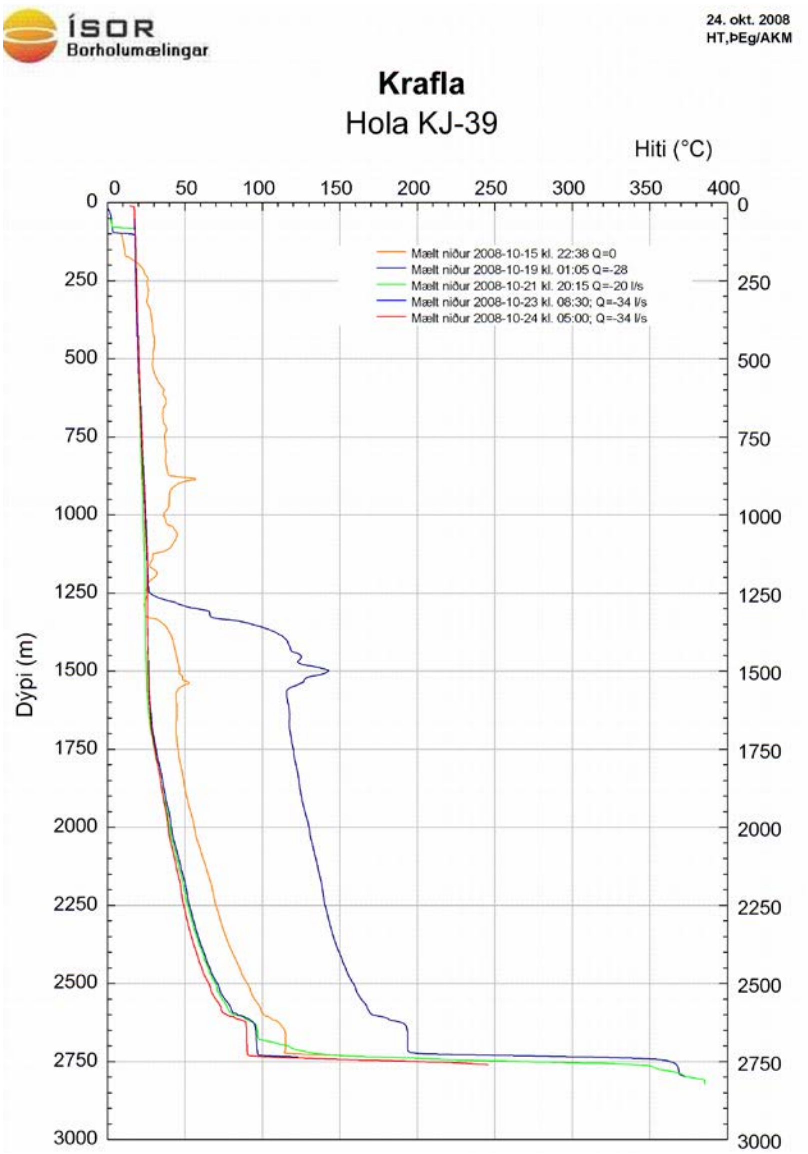

FIGURE 9: Temperature logs of well KJ-39 (From: ISOR database)

FIGURE 10: Well KJ-36 blowing (From: Thorhallsson et al., 2008)

9. ELEVATION CHANGES

Elevation changes and horizontal displacements defined by GPS, inSAR and levelling measurements. Geophysics has the means of measuring accurately vertical and horizontal changes. It has been a common practice in volcanalogy for a long time to measure elevation changes on volcanoes as inflation may indicate magma accumulation. This is also important in surveillance of geothermal fields which may subside due to exploitation if recharge does not make up for fluid production. In recent years satellites have made it possible to register horizontal displacements also (Stamps et al., 2008).

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