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Restoration from a Large Scale Steam Explosion at the Well Site of the Onikobe Geothermal Power Station

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ABSTRACT

The Onikobe single-flash steam turbine geothermal power plant, recent nominal output 15MWe (gross), has been supplying electricity to the grid since 1975. Numerous natural geothermal surface manifestations were present in the field prior to development. New fumaroles accompanied by hot liquid discharges spontaneously appeared at the well site on 8 September 2010. The fumaroles continued to grow until a large scale steam explosion occurred on 17 October 2010. A large steam cloud with entrained solid explosion products rose high into the air. A crater formed and the Well 128 wellhead became submerged in the crater-lake. Two other production wells were engulfed in the crater. Monitoring of surface and subsurface condition with vibrometers, seismographs and tilt meters was started after steam explosion in order to detect hazardous sign of the next steam explosion and to keep safety work in the wellfield. Fluid sampling was performed using a pilotless helicopter, and results of the chemical analysis of the fluid showed that the fluid in the crater was identical to production Well 128 fluid. This suggests that Well 128 was damaged by the steam explosion incident, and that the residual flow from the crater-lake afterwards could be due to a casing failure in Well 128. Steam and hot water had been discharging until a relief well encountered Well 128. Steam leak from other engulfed Well 138 ceased by other relief well. This paper describes the sequence of events, the probable causes, monitoring activity and relief wells drilling which finally succeeded in ceasing discharge.

1. INTRODUCTION

The Onikobe geothermal field is located in the Backbone Range of northern Honshu Island, Japan (Figure 1) within the Onikobe caldera (2.7-1.7 Ma; Yamada, 1988), which measures roughly 9 km (north-south) by 7 km (east-west). Pleistocene post-caldera volcanism has also taken place. The more recent Katayama structural dome (3 km by 2 km) occupies the southeastern part of the Onikobe caldera. The Katayama Depression, a triangular topographic depression (1.5 km by 0.5 km) which has formed on top of the dome, is interpreted to be a downfaulted block resulting from extensional stress across the dome. The faults are believed to provide the vertical fluid conduits which charge the Onikobe geothermal reservoir.

The presence of active natural geothermal surface manifestations in the area (fumaroles, hot springs, strong alteration zones, and high shallow subsurface temperature gradients) prompted exploration and the selection of Onikobe as a geothermal power plant site. The fumaroles emit substantial hydrogen sulfide gas. Sulfur mining was practiced in the area prior to development of the geothermal power station.

Two fluid populations are encountered in the deep part of the Onikobe geothermal reservoir, one neutral (pH = 6.7-7.8) and the other acidic (pH = 3). The acidic fluid has higher concentrations of acid-sensitive constituents (Mg, Fe, Pb, Zn) and Cl compared with the neutral fluid. There is a strong correlation of low pH with high concentrations of acid-sensitive constituents and Cl (Truesdell and Todaka, 2004).

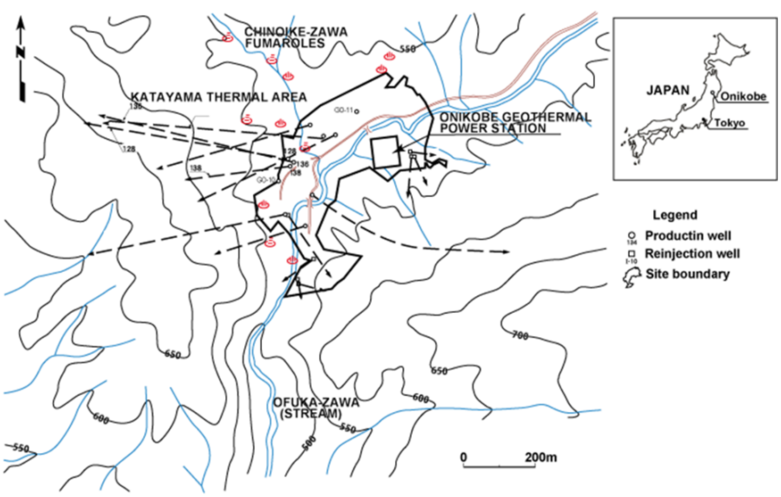

Figure 1: Map of the Onikobe geothermal power plant and wellfield.

Starting in 1963, Electric Power Development Co., Ltd. (J-POWER) drilled exploratory wells at the site, within the Katayama depression. Extremely acidic fluids were encountered in two of the vertical exploratory wells. Deviation drilling was employed to increase steam production while avoiding acidic fluids just beyond the power plant site. There are three wells (128, 136 and 138) located near the steam explosion described in this paper. Well 128, completed in 1980 to a total depth of 1255 m, was the second deviated well drilled at Onikobe.

Well 128 produced neutral fluids at first, but over time the discharge became more and more acidic (Figure 2). The well has multiple feedpoints, and the shallowest feedpoint is in acidic alteration zones. The stable shut-in temperature profile suggests boiling in the reservoir at shallow depths near the well.

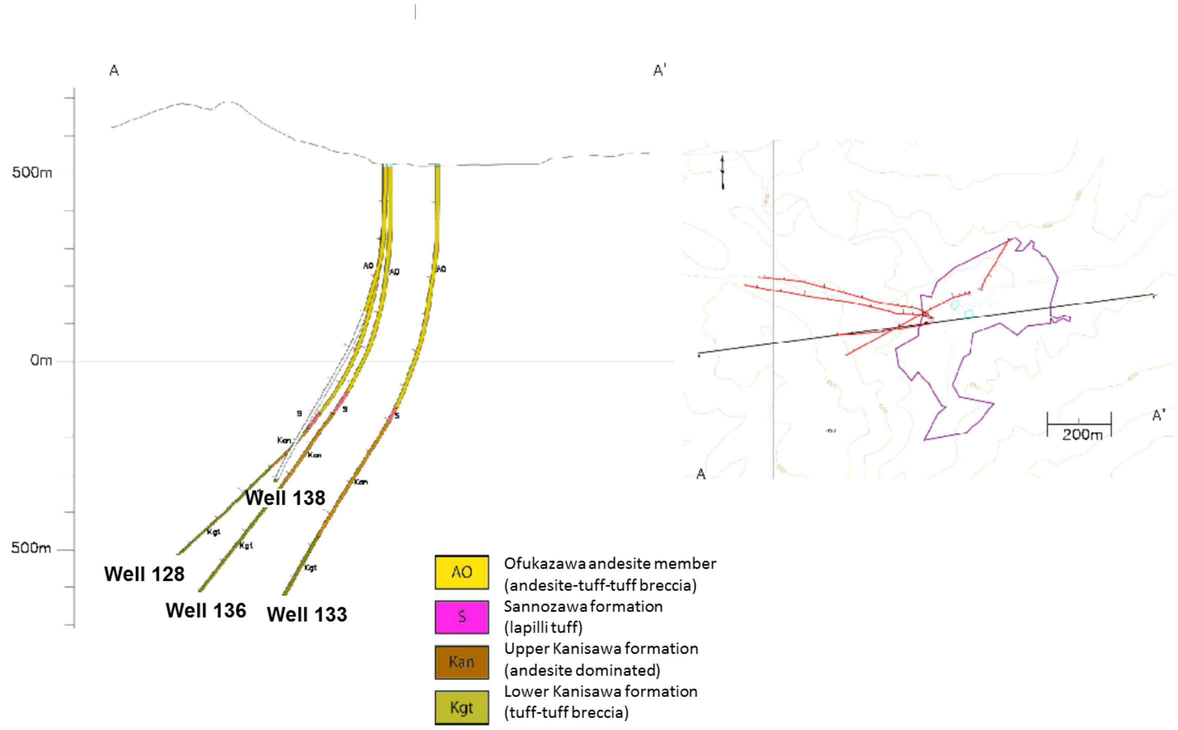

Figure 2: Geological column of Well 128, 136 and 138.

Well 136 was deviation-drilled in 2001 to a total depth of 1334 m into the neutral-fluid part of the reservoir. Well 138 (drilled in 2006; to a total depth 915 m) was also deviated, but encountered acid fluids. Therefore duplex stainless steel was used in the upper part of the production casing of Well 138 to resist corrosion.

2. LARGE WELLFIELD STEAM EXPLOSION

2.1 Evolution of thermal manifestations

Two small geothermal manifestations were first observed on 8 September 2010 near Well 128. These spontaneous new manifestations discharged small amounts of both steam and hot water. Such occurrences were not unusual at Onikobe, since numerous such manifestations were present prior to field development and similar phenomena had appeared and disappeared from time to time during the field's long production history. It was decided to monitor these new discharges carefully, and they continued for flow for about a month without significant changes.

The thermal activity increased noticeably on 8 October 2010, just one month after it was first observed. Steam, hot water, mud and small stones were expelled near Well 128. The well's concrete cellar was first surrounded by erupting steam and then collapsed. Well 128's secondary wellhead valve was closed by remote control, but the manual primary wellhead valve remained fully open. The (manual) primary and (electrically-controlled) secondary valves of adjacent Well 136 and Well 138 were all successfully closed, maintaining well control.

The electrical output of the power station declined because of the loss of steam supply from these three wells. Well 128's wellhead pressure remained about 1.5 MPa at this stage. Well 128 was known to normally maintain positive wellhead gas pressure under shut-in conditions, but a pressure-gauge port at the wellhead had been damaged and steam was escaping through the port into the atmosphere.

The next plan was to inject cold water into Well 128 in order to reduce the wellhead pressure safely. But since Well 128 had been engulfed by the uncontrolled discharge from the fumaroles, the first problem to be solved was to provide access to the wellhead. Heavy construction equipment was used to drop 134 dump truck loads of coarse gravel into the discharging manifestations to act as ballast and maintain wellhead access.

On 15 October, an attempt was made to pump cold water into Well 128 through a six-inch bleed valve downstream of the still-open primary wellhead valve. This failed to reduce the wellhead pressure. To try to achieve a higher injection rate and pump pressure, we next began connecting an injection pump to the two-phase line while continuing to pump cold water through the bleed valve.Subsection headings should be capitalized on the first letter.

2.2 Steam explosion

Then, a large destructive steam explosion abruptly occurred on 17 October 2010. According to witnesses, at first white steam shot upward to a considerable height, then the cloud darkened because of the entrainment of soil and rocks (Figure 2) accompanied by a rumbling of the ground. The erupting solids consisted of a mixture of subsurface materials together with the coarse gravel that had been previously emplaced to maintain wellhead access. Fine eruption products also rose and fell in surges.

Figure 3: Photograph of the moment of steam explosion taken from 5 km west of the wellfield. A mountain ridge hides center of the explosion (Akasaka et al., 2011).

The post-explosion crater rim is 45 m in diameter, and the Well 128 wellhead is submerged within it. Well 138 is on the crater rim, and Well 136 protrudes from the hot water surface within the crater.

Fortuitously, a photograph was taken from 5 km west of the Onikobe power station at the moment of the explosion (Figure 3). Analysis of the photograph indicates that the dark-colored eruptive materials to the north rose about 250 m above the crater. The grey-colored materials to the south rose more than 400 m.

The subsurface rocks and soils fell preferentially to the south. The coarse gravel ejecta fell near the crater, somewhat to the east. The fines fallout pattern was more widely distributed, and preferentially collected in regions of low earth surface topography (river and stream beds). Based on the estimated area and thickness of these deposits, the total volume of erupted fines is estimated as about 10,000 m3, which is comparable with volumes ejected from ordinary hydrothermal eruptions brought about by volcanic activity.

A relatively high temperature surge of fine materials was witnessed by several Onikobe workers and recorded by meteorological observation equipment. The traces of particle impacts on the pipelines, the distribution of the rubble erupted from the subsurface and the distribution of particle sizes imply that the explosion was a gas jet eruption oriented at a considerable angle from the vertical and directed towards the south. Examination of the ejected solids suggests a shallow subsurface origin (less than 40 m).

Four members of the field crew were preparing Well 128 for cold-water injection operations when the explosion occurred. Two successfully escaped unharmed, but one died and the other was severely burned.

2.3 Subsequent events

Discontinuous emissions of steam and muddy water continued in a geyser-like fashion for a time after the explosion. The strength of these eruptive discharges declined gradually and finally ceased altogether on 23 October, six days after the main explosion. Continuous fluid discharges were observed subsequently. No direct measurements are available, but these have been estimated to be roughly 5 – 10 tons/hour of steam and 60 tons/hour of hot water by observers (Figure 6). The overall size of the crater has not changed significantly since the explosion, although the upper parts of the crater rim have collapsed due to erosion. The discharge became intermittent starting on 18 January 2011.

Crater water sample analyses suggest that about 3/4 of this water consists of separated water from the well. The composition was the same on 29 October and on 24 February, suggesting that geothermal fluid has been leaking up Well 128 since the steam explosion.

3. PROBABLE CAUSES OF THE EXPLOSION

In the absence of definitive data, we hypothesize that the subsurface sequence of events as follows.

1) A shallow high-pressure chamber first formed, supplied by hot fluid from greater depths.

2) Steam started leaking from the chamber to the surface on 8 September 2010.

3) On 16 October, a steam blowout occurred and in-situ boiling was accelerated due to the resulting pressure drawdown.

4) On 17 October, an explosive steam eruption took place due to nearly instantaneous flashing of substantial amounts of hot water to steam.

5) Since that time, a stable discharge of hot water and steam has continued.

We have two competing hypotheses about the reason why the shallow high-pressure chamber formed:

1) Natural fumaroles are common in the area, and subsurface temperatures are high even at shallow depths. Thus, the chamber may have formed naturally, the pressure may have gradually built up within it, and finally a catastrophic rupture took place.

2) Since the chamber formed near a production well, the presence of the well may have played a role. A damaged well casing could have caused undetected slow steam leakage into the shallow subsurface over a long period of time, gradually forming and pressurizing the underground high-pressure chamber.

4. MONITORING FOR GEOTHERMAL ACTIVITY

Based on experts' recommendations a surface and subsurface monitoring program was begun after the steam explosion occurred. Also, discharging fluid samples are being acquired and analyzed chemically to detect any changes in water origins. In order to observed vary of tremor phenomenon which is related to evolution of steam explosion, vivrometers, three-component seismographs and tilt meters were chosen. Location of monitoring stations were indicated in Figure 4.

4.1 Vibrometers

A process of evolution of large scale steam explosion, vibration observed on the subsurface obviously. Vivrometer is used for diagnose of structure of building or environmental monitoring usually. It is able to give objective numeric indices for vibration phenomena. A vibrometer was installed at the beginning of November to detect tremors associated with geothermal activity. More instruments were added over time – at present four vibrometers are operating in the wellfield.

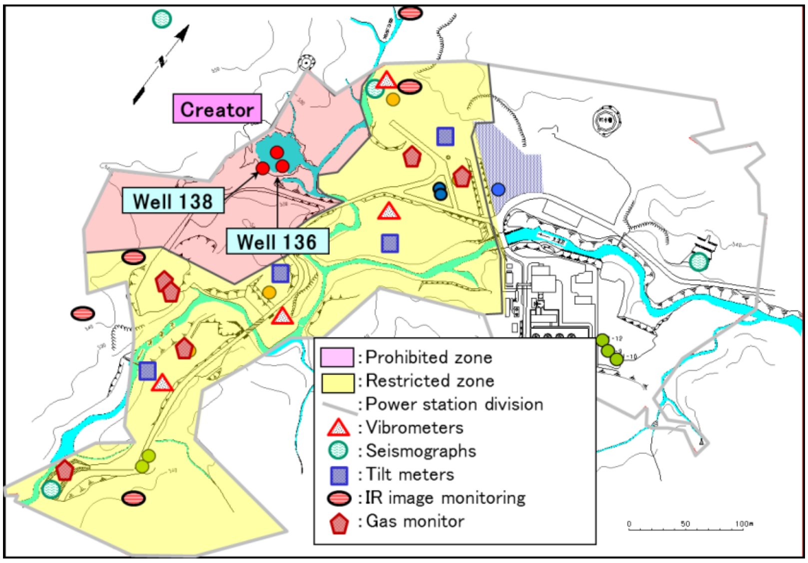

Figure 4: Distribution of monitoring points with classification of working area.

4.2 Seismographs

Early stage of the evolution of steam explosion, like a forming high pressure chamber, accompanied with collapse of formation rock. Seismic events were expected. A three-component seismograph was installed and has been recording since 22 November, and a second three seismograph was added on 14 December. These instruments clearly showed that tremor amplitude decreased after the onset of intermittent geyser-like discharge on 18 January 2011. Relatively large ground noise observed because these four seismographs were located near noisy power plant or steam process facilities. One seismograph was relocated to west of crater in order to optimize distribution of seismic network which enclosed the crater on December 14, 2011. This seismic station buried in subsurface to reduce ground noise. At this moment seismic network was able to estimate hypocenter location and magnitude after seismic event by man hand. However real time hypocenter detection system was need in Onikobe to make alert preventing human from steam explosion. Then four seismographs were added to the network, which located out of site for power station. Thereafter one additional seismograph was installed in a well bore keeping away from ground noise.

Location of seismic network consisted of nine seismographs and estimated hypocenter locations are indicated in Figure 5. Indicated result was estimated automatically but after seismic event. The real time automatic seismic system is able to provide rapid estimation of hypocenter location and magnitude. If forming of pressure chamber progress near subsurface, seismic event might be detected by this system real time.

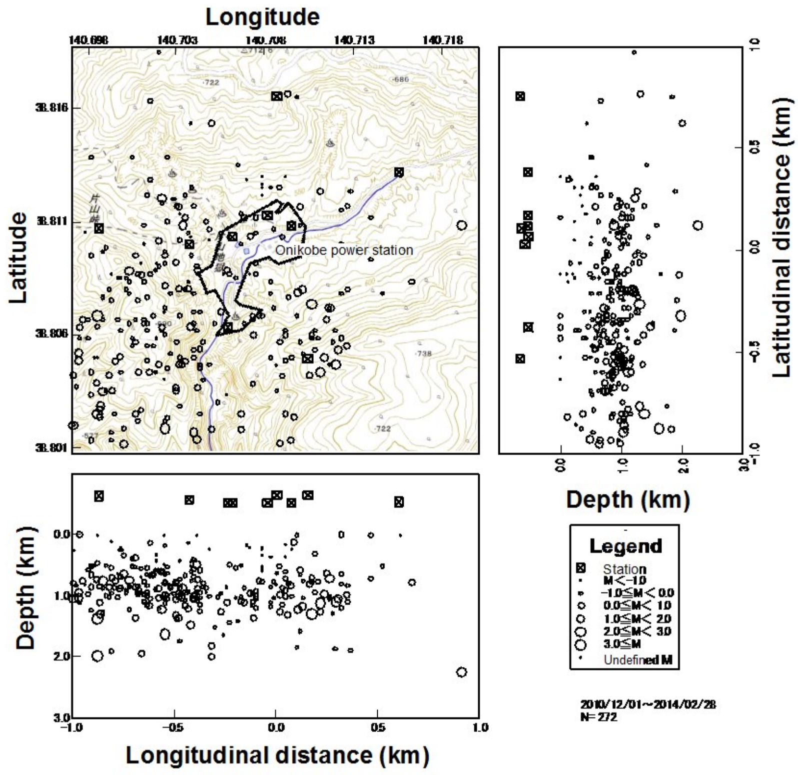

Figure 5: Location of seismic network stations and distribution of hypocenters from December 2010 to February 2014 within 1km distance and 3km depth.

4.3 Tilt meters

Four Pinnacle hybrid tilt meters installed at the bottom of 12 m bore hole on 20 January 2012. Tilt meter is able to detect long term deformation of topography and long wave length tremor. Sensitivity of these tilt meter are enough to be able to observe surface wave of a far earthquakes.

4.4 Chemical component

Self-contained navigation helicopters were used to chemical sampling, aerial photographs and laser mapping. The result of chemical sampling of water in the crater-lake is indicated in Figure 6. Photographs and result of laser mapping indicated that there is no remarkable change in local topography around the crater.

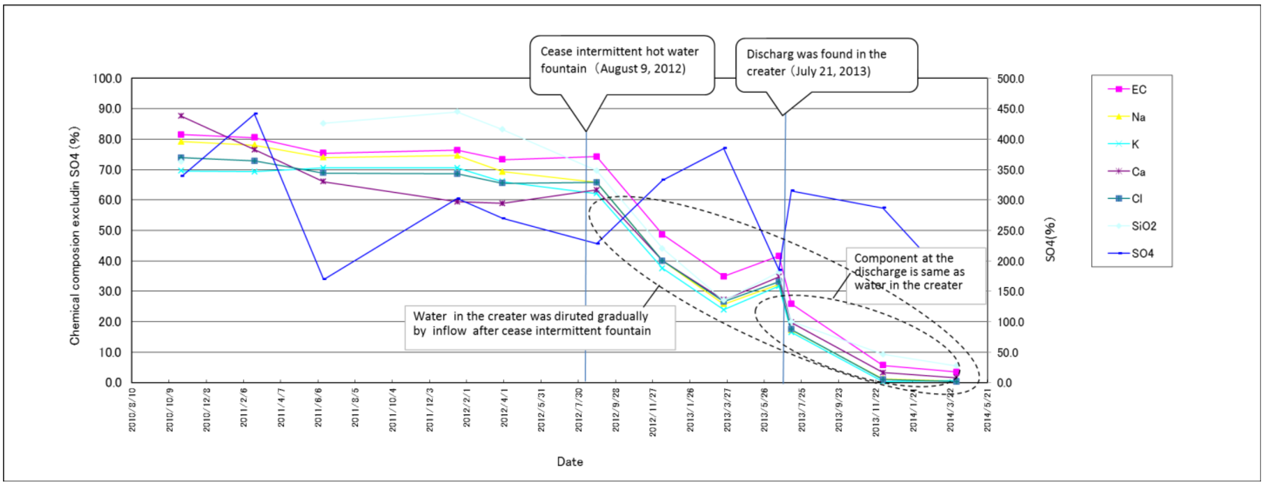

Figure 6: Change in chemical concentration of water in the crater-lake.

5. STEAM LEAKAGE FROM WELL 138

After the large-scale steam explosion, intermittent hydrothermal eruptions about 20 m high were observed for a prolonged period. Hot water eruptions from 5 to 15 m in height were still occurring intermittently in February 2012. Samples taken of the erupting fluids were analyzed chemically, and these analyses reveal fluid compositions that are very similar to those of fluids that had been produced from Well 128 prior to the disaster. We therefore tentatively concluded that the uncontrolled discharges were blowing out from the damaged Well 128 wellhead.

Steam began to leak through near casing head of Well 138 on 9 March 2012. Amount of leakage was observed about several tons/hour by the eye. It was though that strong acid fluid weekend casing until crack occurred. Because of an apprehension of cutting off wellhead of Well 138, protection cover was constructed for preventing for worst situation, that is fall of well head and blowing out. Because Well 138 located in "prohibited" working area, operator-less construction machines were used to make flat ground surface and to install the protection cover.

Figure 7: Steam leaking through casing head just under the closed well head valve of the Well 138 (on 9 March 2012)

6. RELIEFE WELLS

Just after steam eruption, "restricted" and "prohibited" areas were designated within the wellfield from the point of view of preventing workers from victims (Figure 8). For the first step to returning project operations to normal was clearly to regain control over Well 128 and to shut it in permanently.

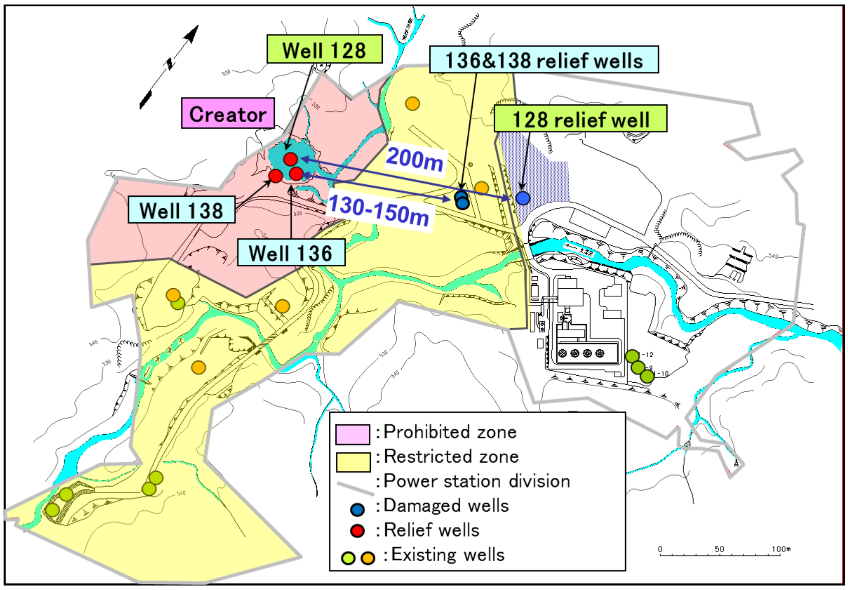

Figure 8: Location map of the damaged wells by steam explosion (red circles) and relief wells (blue circles).

Since the "restricted" and "prohibited" safety zones within the site must be respected. Therefore the relief well was spudded near the power station outside the controlled area approximately 200 meters to the east of the Well 128 wellhead (see Figure 8).

In order to carry out the drilling in accordance with the planed trajectory, Measurement-While-Drilling (MWD) was used below the kick-off point. Ranging to detect magnetic interference was also used to ascertain well location. Considering the possibility of drilling under lost circulation conditions, we used the E-field Gyro MWD. Ranging is generally considered to be about 15 m in a magnetic Casing and we couldn't ascertain the degree of corrosion by acid geothermal fluids at first.

6.1 Sequence of crater-lake events during drilling 128 relief well

As soon as the total loss of circulation occurred at 896 m depth during drilling, the intermittent hydrothermal eruptions at the surface ceased (Figure 9). After that, there were a number of changes in the water level in the crater-lake, masked to some extent by varying amounts of rainfall. When Well 128 was occluded by sidetrack D-4 (after cementation), the crater-lake water level fell to 4.5 m below maximum. This was a major factor that convinced us to drill sidetrack D-5. Since Well 128 was plugged by sidetrack D-5, the water level in the crater- lake has risen due to the inflow by stream water. At present, we think that outflow and inflow are roughly in balance based on monitoring results.

Figure 9: Change of steam discharge from crater (left; 2 June 2012) and after first plugging of Well 128 (right; 18 September 2012), after Takizawa et al. (2013).

6.2 Sequence of steam leakage during 138 relief well drilling

Steam leak from the Well 138 continued after intermittent fountain ceased by 128 relief well. The 138 relief well was spudded in the restricted area approximately 150 meters to the east of the Well 138 wellhead (see Figure 8). About 5 hours after partial loss of circulation occurred at 673 m depth during drilling sidetrack D1c, form like material appeared on the water table of the crater-lake. Amount of leaked steam became low obviously one day after (Figure 10). Form like material was thought from mud component. Decrease of steam leak caused reservoir cooled by low temperature mud water of loss circulation.

Figure 10: Change of steam leakage from Well 138 before relief well affected (left; 26 September 2013) and after (right; 18 April 2014)

7. CONCLUDING REMARKS

A large steam explosion took place near a producing well in the wellfield supplying the Onikobe geothermal power station. There are two possible root causes: (1) that a steam-filled shallow subsurface chamber formed naturally in this highly-active geothermal area and then explosively erupted, or (2) that the explosion was somehow related to production operations. No evidence is available to permit us to distinguish between these possibilities.

Ongoing careful monitoring of both surface and subsurface thermal activity should improve the operational safety of the Onikobe geothermal power station for the future.

Three producing wells were affected from large steam explosion, Well 128 was submerged into the crater-lake, Well 138 located on the crater rim and Well 136 on the crater-lake.

After Well 128 was successfully plugged by the second cement injection through the relief well, discharge from the crater-lake ceased. Also after loss circulation of the relief Well 138 during drilling, steam leakage near wellhead of the Well 138 decreased remarkably. Relief wells contribute to cease the damaged wells by large scale steam explosion and to make safe working circumstances in the wellfield of the Onikobe geothermal power station.

8. ACKNOWLEDGEMENTS

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