GEOTHERMAL RESERVOIR MONITORING BY CONTINUOUS SELF-POTENTIAL MEASUREMENTS

K. YASUKAWA[1], T. ISHIDO[1], I. SUZUKI[2], E. KUSDINAR[3], M. TAKAHASHI[1] & H. MURAOKA[1]

[1]Geological Survey of Japan AIST, Tsukuba, Japan
[2]JMC Geothermal Engineering Co. LTD, Iwate, Japan
[3]Directorate of Volcanology and Geological Hazard Mitigation, Bandung, Indonesia

SUMMARY – Self-potential (SP) monitoring was conducted at two geothermal fields, Mori (Japan) and Mataloko (Indonesia), with the purpose of detecting changes of fluid flow system in reservoirs caused by well operations. Surface SP was monitored at eight observation points across the reservoir during shut-in and draw-down of the wells at Mori, and at sixteen observation points around an exploration well during its flowtests at Mataloko. To solve the problem of reference points for the measured potential, a concept of relative SP, defined as the differential from the average SP of all monitoring points, was introduced. The advantage of relative SP is clarified through numerical simulations. Results of the field observation show that specific changes of relative SP at each monitoring point were detected correspondingto the well operations. Relative SP monitoring can be applied to investigate both the extent of a reservoir and its hydrological conditions.

1. INTRODUCTION

Theoretically, continuous SP observation can be applied for reservoir monitoring, assuming that the main cause of the SP anomaly is streaming potential, in a similar manner as the micro-gravity monitoring. However, no practical procedure has been developed for the interpretation of continuous SP data, in spite some recent attempts of SP monitoring.

One of the difficulties in interpretation of continuous SP data is that there are many causes which can perturb the surface SP. These include artificial noises, magnetic field perturbation caused by solar activity, rainfall effect, etc. It is difficult to identify the SP change caused by the subsurface fluid flow. In addition, it is usually almost impossible to find a reference point where the electric potential can be assumed to be stable. Finding an ideal reference point is always an obstacle for SP monitoring.

This paper presents results of continuous SP observations conducted in the Nigorikawa basin, Hokkaido, Japan and in the Mataloko geothermal prospect, Indonesia. In both areas, SP changes were monitored over the period of well operations at several surface points around the production zones. For each monitoring point, changes of "relative" SP was plotted versus time, assuming that the average SP between all monitoring points is always zero. Advantages of such a "relative" SP will be shown in the next section through some simulation results. Attempts to reduce the SP perturbation caused by external noises will also be explained. Changes of relative SP during well operations reflect the hydro-geological characteristics of both the reservoir and the individual monitoring point. The effectiveness of relative SP monitoring will also be discussed in this paper.

2. ADVANTAGES OF "RELATIVE" SELF-POTENTIAL OBSERVATION

As mention previously, setting of a reference point may be a problem for a reservoir monitoring using SP observations, since no ideal reference point exists in a real field. Changes of SP with time would occur at any selected reference point, which will perturb the SP data recorded at the observation points. To reduce this problem, a concept of "relative" SP was introduced.

Relative SP is defined as differential from the average of all observed SP values at the time of the measurement. There is an advantage in using such a relative SP for characterization of individual observation points, even when there is no SP perturbation at the reference point (an ideal case). Fig. 1 shows a 2D reservoir model for a simulation of geothermal fluid production and injection. Production begins at time t = 0 and 75 % of the produced fluid is injected into a shallower part of the reservoir. The number of the assumed observation points (solid triangles in Fig. 1) is 25.

Fig. 2 shows changes of absolute SP, which would be obtained with a reference point at infinity, simulated by the PTSP computer program (Yasukawa et al, 1993). The effect of injection is larger than that of production because significant amount of fluid is injected into a shallower part, resulting in a decrease of SP at all observation points across the reservoir. Similar results were obtained assuming a reference point near the edge of the observation range (distance x = -1.0 or 1.5 km).

Fig. 3 shows changes of relative SP for the same model. Over the production zone (left side of Fig. 1, at x = -900 m, -600 m, -300 m and 0 m), relative SP increases with time. Over the injection zone (x = 300 m, 600 m and 900 m), it decreases with time. Fig. 4 shows relative SP profiles at time t = 0 to 1 year. Different behaviours of production and injection zones can be easily identified in Fig. 4.

To apply the relative SP technique, the number of observation points must be sufficient to cover a "target area". In a typical case, an area of diameter –5d (where d is the depth of SP source) should be covered. As shown in Figs. 5 and 6, relative SP profiles are still useful for fewer observation points, if the points are distributed over the whole target area with equal spacing. However, the number of observation points must be large enough to avoid a problem of spatial aliasing (in the present case, the minimum number is four; see Figs. 6 and 7). A large number is also desirable to get a good average value with a high signal to noise ratio (SM).

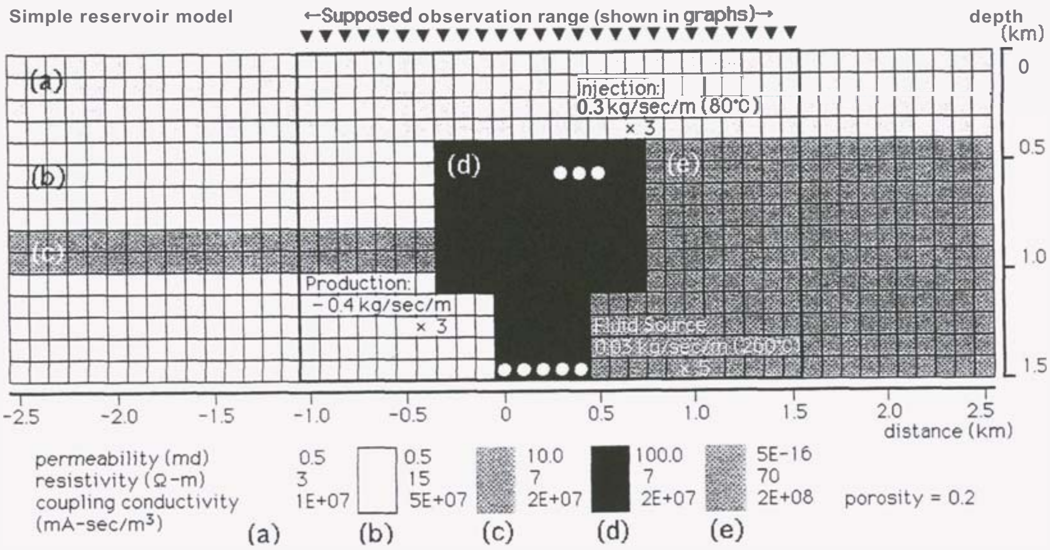

Fig. 1 Reservoir model.

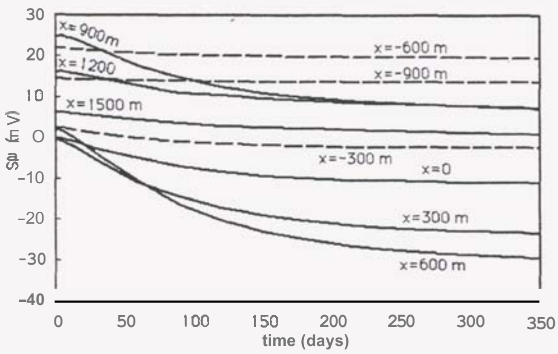

Fig. 2 Simulated changes of absolute SP.

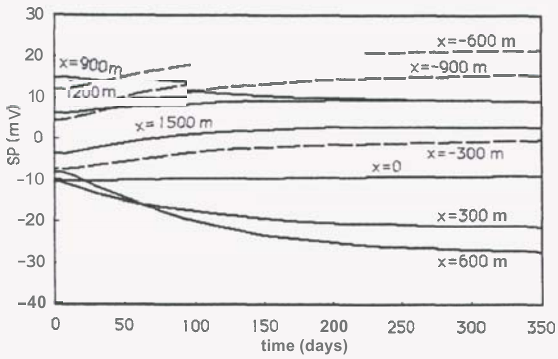

Fig. 3 Simulated changes of relative SP.

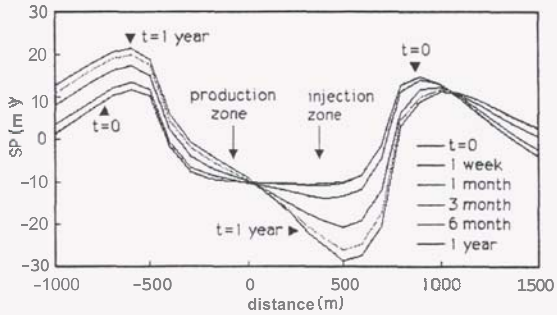

Fig. 4 Realative SP profiles calculated for 25 observation points.

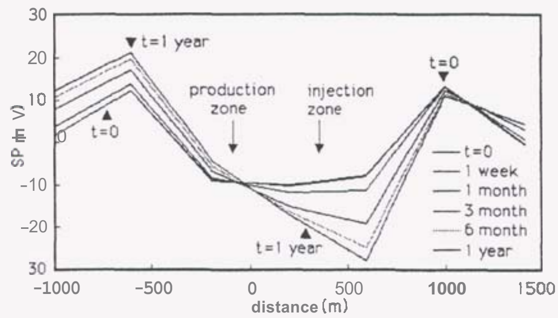

Fig. 5 Relative SP profiles calculated for 7 observation points.

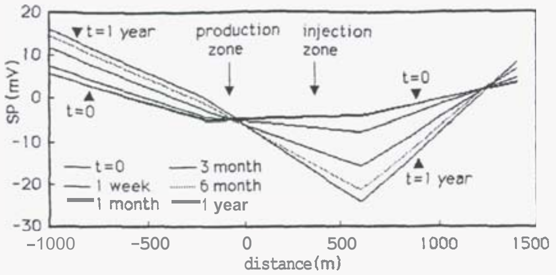

Fig. *6* Relative **SP** profiles calculated for **4** observation points.

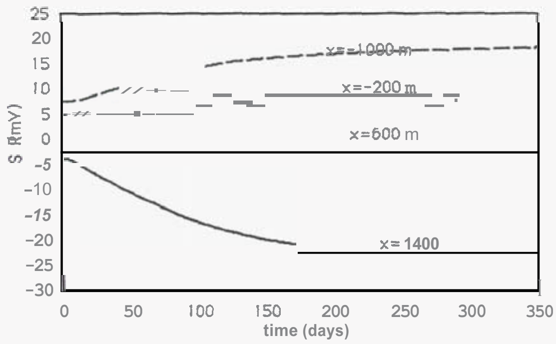

Fig. 7 Simulated change of relative SP for four observation points.

3. SP OBSERVATION AT THE MORI GEOTHERMAL FIELD

Mori geothermal field is located in the Nigorikawa Basin, Hokkaido, Japan (Fig. 1). According to Ando (1983), this basin is composed of a small Crater Lake type caldera with a diameter of **3** km. An active hydrothermal system is identified near the northern **part** of caldera wall (Ando, **1983).** The geothermal reservoir existing in the caldera is a liquid-dominated system and hot spring discharges are identified in the northern part ofthe basin.

In this area, extensive geothermal exploration had been done since 1972 by Japan Metals and Chemicals *Co.* Ltd. (JMC) and Dohnan Geothermal Energy Co. Ltd. **(DGE)** ,resulting in the construction of **Mori** geothermal power plant which has been operating since 1982 with installed capacity of 50 MW. The depths of the production and injection zones are 600-2400 m and 200-2000 m, respectively.

A continuous SP monitoring was conducted from July 31 to October 10, 2000 at eight monitoring points. All production and injection wells were shut-in for a month starting on **August 3** for the annual maintenance of the Mori geothermal power plant. The SP monitoring was aimed to detect any changes of subsurface fluid **flow** system caused by reservoir perturbations associated with the shut-in and draw-down operations of the wells. The surface SP monitoring points are located inside the caldera, except for D5 in the east. These points are almost aligned, straddling the reservoir approximately from west to east (Fig. **8).**

Figs. 9 to 13 show the relative **SP** changes together with rainfalls in the Nigorikawa basin. The vertical lines indicate the times when the wells were shut-in (August **3)** and re-started (August 26 to 29).

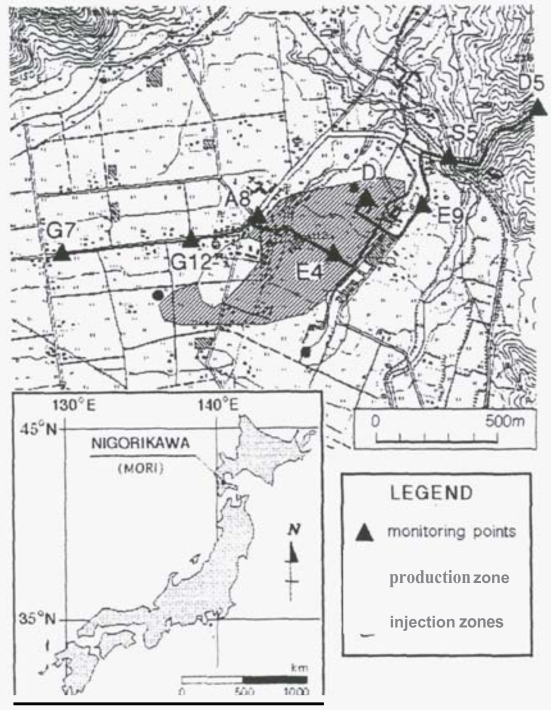

Fig. **8** Distribution of production and injection zones and SP monitoring points in the Nigorikawa basin.

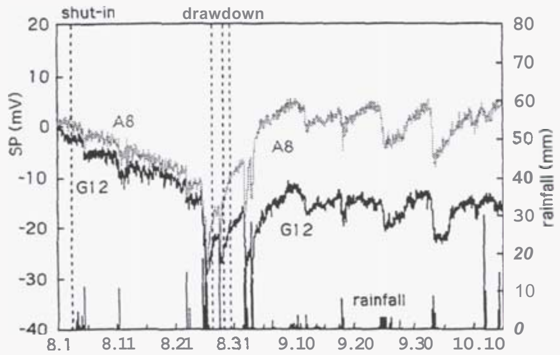

Fig. 9 Observed SP changes at G12 and **A8.**

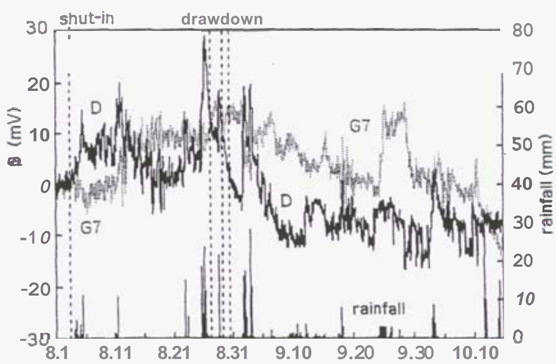

Fig. 10 Observed **SP** changes at G7 and D.

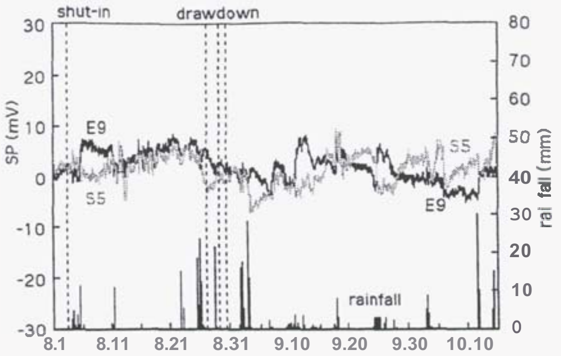

Fig. 11 Observed SP changes at E9 and S5.

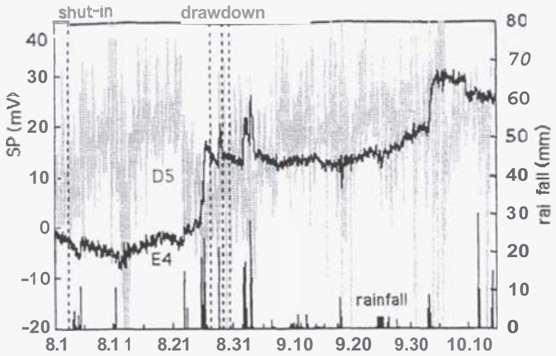

Fig. 12 Observed SP changes at E4 and D5.

The relative SP in these figures was calculated using the average of seven points, excluding D5 because of its considerable high-frequency noise. Note that for most of the observation points, the common external noise of the relative SP values was reduced using a procedure which will be discussed in **4.1.**

G12 and **A8,** both located near the centre of the basin, show similar characteristics (Fig. 9); the SP decreases after shut-in and increases after draw-down. G12 is located outside the injection zone while **A8** is close to both injection and production zones. Hence, the **SP** variation at A8 shows the characteristics of outside the injection zone and/or inside the production zone. These two categories have a similar tendency of SP changes, **i.e.** a decrease during shut-in and an increase after draw-down. The more drastic SP rise at **A8** in comparison to that at G12 after the draw-down may be caused by the combination of these two effects at A8. Clear responses immediately after rainfalls are identified in Fig. **9.** The effect of rain can be explained by a simple vertical infiltration.

SP variations at G7 and D (Fig. 10) show opposite characteristics to those at G12 and A18; the SP increases during shut-in and decreases after draw-down. G7 is located outside both the production and injection zones. Since total amount of production is larger than injection for the whole system, the effect of production would be dominant. Thus the SP variation at G7 can be characterized as the behaviour outside the production zone. Although D is located inside production zone, it shows the characteristic behaviour of outside the production zone. It is suggested that D may have a local hydrological setting similar to that of outside the production zone. The effect of rain is detectable at D but not at G7.

SP variations at E9 and *S5* (Fig. 11) show similar characteristics to those at G7 and D but the rate of changes is smaller. The effect of rain is unclear at both monitoring points, since rainfall near the border of the basin may cause shallow lateral flows besides the vertical infiltration.
Fig. 12 shows the monitoring results for E4 and D5. The **SP** at E4, located in the middle of production zone, increases immediately after draw-down. The effect of rainfall can also be seen at E4. The **SP** at D5, located outside the basin, has no clear response to the well operations but it has a significant high-frequency drift, amplified by high subsurface electrical resistivities. This result suggests that the reservoir range is limited inside the basin and that there is no hydrological connection between the areas inside and outside of the basin.

4. SP OBSERVATION AT THE MATALOKO GEOTHERMAL PROSPECT

Mataloko geothermal prospect is located at central Flores, East Nusa Tenggara, Indonesia, near Bajawa town (Fig. 13). Geological, geochemical and geophysical surveys have been conducted around this area as a cooperation project between Indonesia and Japan (Muraoka, 2002). An SP survey was made at Mataloko in 1998 (Yasukawa et al, 2000). The highest SP anomaly in Mataloko area was observed at the main geothermal manifestation area along the Wae-Luja river (Fig. 13). **A** shallow exploration well MT-2 was drilled during the end of 2000 as part of this project, and it reached the reservoir at 162 m depth (Sueyoshi et al., 2002).

SP monitoring studies were conducted in January and July 2001, during the flow-tests of **MT-2.** In January, only the shut-in was monitored because of some setting problem, while in July the monitoring period covers both the start of production and shut-in times (Fig. 14). The produced fluid was wet steam in January but it was dry steam in July after a long-term flow test. Fig. 13 shows the location of the SP monitoring points. In January, the **SP** variation was monitored at eight observation points (Nos. 1 to *8).* Eight additional monitoring points **(A** to H) were established in July to cover wider area.

4.1 SP monitoring in January 2001

Fig. 15 shows the relative SP observed in January. The relative SP was calculated using the average of seven points, excluding point No. **2,** which was located very close (–15 m) to the wellhead of MT-

2 that its behaviour would be strongly influenced by the presence of well-casing.

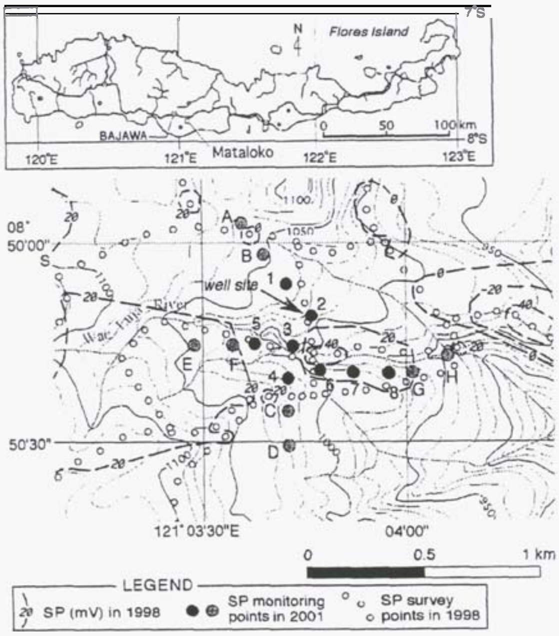

Fig. 13 Map of SP monitoring points at Mataloko.

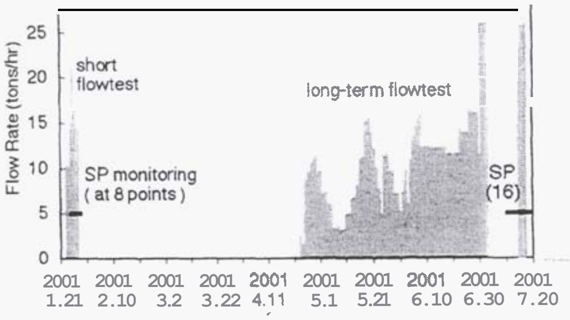

Fig. 14 Flow rate of well MT-2 and SP monitoring terms at Mataloko.

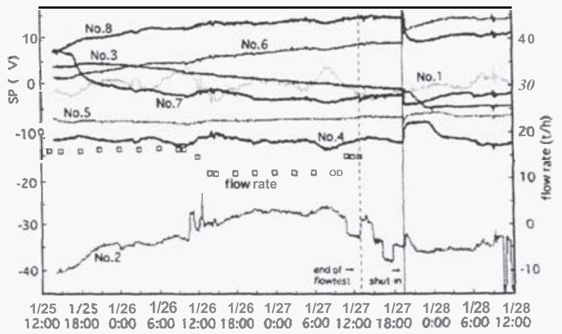

Fig. 15 Relative SP change **at Mataloko in January** 2001

The **SP** at station No. 2 slowly increased with production, but the increase stopped after the decrease of flow rate on January **26** and it changed to a decrease after the shut-in on January **27.** The short-term peculiar changes observed around noon on January **26, 27** and **28** are thought to be caused by wellhead operations. The **SP** at all monitoring points showed quick responses to the shut-in of the well at 19:30 on January **27.** At station No.3, located at the main natural discharge area, changes of the **SP** trends were also observed after the shut-in.

Although during the measurement period it rained everyday for a few hours in early afternoon, effect of the rain on **SP** was not observed. The effect of common external noise was observed only at stations No. 1 and No. **4,** which are located at higher elevations. **SP** drifts for the first few hours of the observation are due to change in the electrode contacts with the ground.

4.2 SP monitoring in July 2001

The second **SP** monitoring in July was conducted at sixteen observation points, over a short term flow-test carried out after a three-month-long flow-test starting on April. The reservoir condition might have changed from that in January.

The relative SP changes observed during this second survey along monitoring points aligned in the north-south direction are shown in Fig. 16. Relative SP values are calculated based on the average of **14** points, excluding points No. **2** and No. *6* (No. **6** is excluded because of lack of the early-time data). In Fig. **16,** common high frequency variations are identified, which also appear for at the points aligned from east to west. Such variations are thought to be caused by telluric current induced by external geomagnetic variations. The waveform of "external noise" shown in Fig. 16 is calculated from the 14 observation data, which can be used to extract the external noise.

The graphs in Fig. **17** are obtained by reducing the external geomagnetic noise from each curve in Fig. 16. Change of **SP** trend at the beginning of production was observed at stations No. **2,** No. **3,** No. **4,** No. 5, C, E and F. No clear change occurred after shut-in at these points. At stations No. **8, A,** B, D, G and H, SP trend changed when production started and returned back to the earlier trend after shut-in, although the difference is quite small. **At** stations No. 1, No. **6** and No. **7,** no response to the well operation was observed.
SP responses to shut-in of the well were not clearly identified in July except for station No. **2.** On the other hand, the effect of rainfall which were not detected in January is clearly identified at all monitoring points in Fig. **8.**

4.3 Discussions

SP responses to the shut-in of the well at Mataloko in January and in July 2001were quite different. In January a sharp SP change occurred after shut-in at all monitoring points while no such clear change was observed in July. The reason is that the flow test in January was conducted immediately after the well completion, while in July was made after a long-term flow-test.

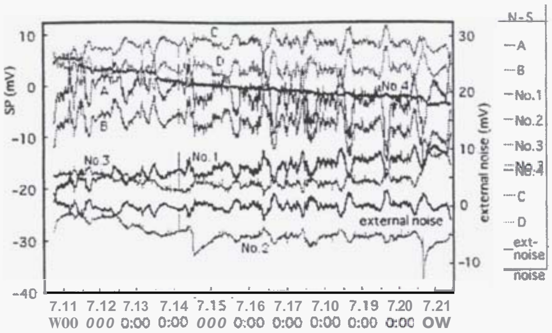

Fig. 16 Relative SP change observed at Mataloko in July 2001 along **N-S** line, showing the common external noise.

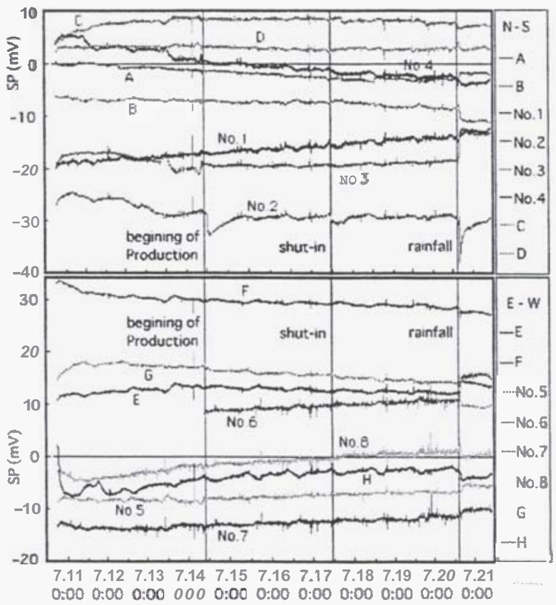

Fig. 17 Relative SP change at Mataloko in July 2001 (common external noises have been removed).

In January, a substantial amount of liquid-phase fluid was present in the reservoir, and its motion was changed by the well operations, resulting in quick **SP** changes due to streaming potential. However in July, considerably less liquid was remaining in the reservoir and, therefore, no detectable change in streaming potential occurred. This is consistent with the fact that the produced steam in January was wet while in July it was dry.

The effect of rainfall on **SP** was quite large in July while it was not identified in January. In July (dry season), rainfall causes shallow resistivity change, resulting in **SP** change while in January (rainy season) when it rained almost everyday, the ground was already saturated and no **SP** change occurred.

The influence of external geomagnetic variation is considerably larger in dry season because of higher electrical resistivity of the shallow ground. This is consistent with the occurrence of external noise in January at higher elevation where the ground may not be completely saturated.

5. CONCLUSIONS

Simulation result shows advantages of relative **SP** monitoring to clarify hydrological characteristics of each monitoring point. Relative SP profiles are still useful where observation points are fewer, if the points are distributed over the whole target area with equal spacing.

Self-potential (SP) monitoring studies were conducted at the Mori and Mataloko geothermal fields. Mori field is liquid dominated, whereas Matakolo field is vapour dominated. The SP monitoring at Mori detected the reservoir extent and the individual characteristics of observation points. At Matakolo, changes of reservoir conditions before and after a long-term flowtest were detected by the SP measurements. **A** seasonal change of the effect of rain can also be noticed in the **SP** records. These studies have shown that relative SP is promising **to** investigate the extent of a geothermal reservoir and its hydrological conditions.

6. ACKNOWLEDGEMENTS

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