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Prevention and dissolution of anhydrite deposit using chemical agents for production wells at the Mori geothermal field, Hokkaido, Japan

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ABSTRACT

Deposition of scale minerals, such as calcite, anhydrite, and smectite (Mg-silicate), has been found in production wells in the Mori geothermal field. The most serious decline in steam production was caused by calcite deposition occurring around a boiling depth in wellbores. The calcite deposition has been inhibited by injection of a sodium polyacrylate solution as a scale inhibitor several hundred meters below the boiling depth through downhole tubing.

Deposition of anhydrite, which occurred at a greater depth than that of calcite, also reduced the production of deep wells having shallow and deep feed zones. We concluded from results of well loggings and mineralogical studies on scale samples that the anhydrite deposition was induced by a water entering from the shallow feed zone, and that the polyacrylate solution could prevent anhydrite deposition. The injection point of the inhibitor solution was accordingly lowered below the shallow feed zone, and this setting of the injection has been highly effective against both of the calcite and anhydrite depositions.

In addition to the prevention method, chemical dissolution of anhydrite deposit was conducted in a production well. A chelating agent, a sodium salt of EDTA, was injected as a dissolving agent in the operation of chemical dissolution. This operation effectively dissolved the deposit and provided a recovery of the production with much less cost than a mechanical workover.

1. INTRODUCTION

The Mori liquid-dominated geothermal field is located in the southern part of Hokkaido, Japan （Figure 1）. The Mori geothermal power plant started its power generation of 50 MWe with six production wells and seven reinjection wells in 1982. Ten production wells and nine reinjection wells are presently used.

The geothermal reservoir is located in the Nigorikawa caldera, which was formed about 12,000 years ago (Figure 2; Yanai et al., 1992). The subsurface geological structure of the reservoir has been studied precisely through the drilling of 79 wells (Figure 2b). The structure is characterized mainly by a funnel-shaped caldera, which is about 3 km in diameter at the surface (Figure 2a). The vertical vent of the caldera with the diameter of 300–500 m extends beyond -3,000 m ASL. The inside of the caldera is composed, from the top down, of 1) an alluvial deposit, 2) a lake deposit, 3) a vent-fill deposit, and 4) post-caldera intrusive rocks. The intrusive rocks consist of hornblende-bearing two-pyroxene andesite, hornblende andesite and hornblende dacite, filling the vent below ca. -2,000 m ASL (Kurozumi and Doi, 1993 and 1994). Outside of the caldera, the following formations are found from top to bottom: 1) the Ishikura Formation (pyroclastic rocks from the Nigorikawa volcano; Quaternary), 2) the Ebiyagawa Formation (andesite, tuffaceous rocks, shale, and conglomerate; Tertiary), 3) the Kamiiso Group (limestone, pelitic and psammitic rocks, chert, and greenstone; thermally metamorphosed pre-Tertiary).

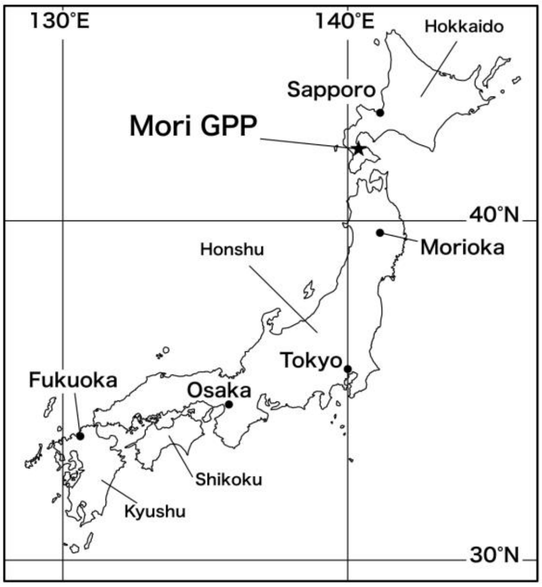

Figure 1. Location of the Mori geothermal field.

Geothermal fluid has been extracted from a fracture zone, which is located in the depth interval from 2,400 to 3,200 m MD (-2,200 to -2,950 m ASL), in the caldera wall, and from another fracture

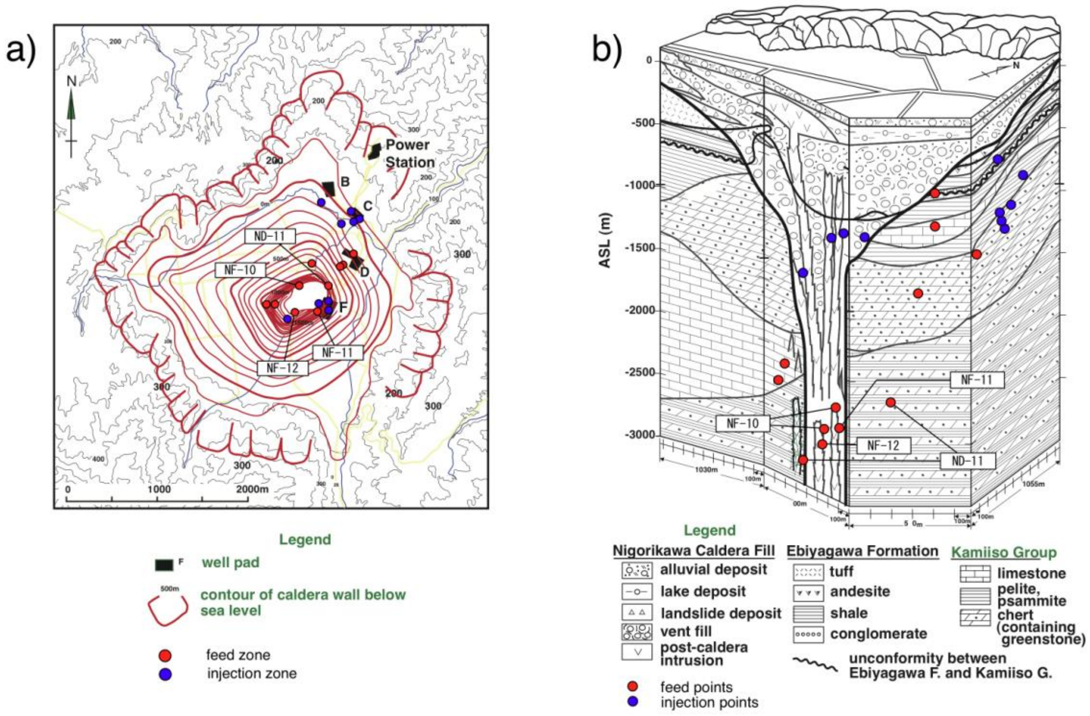

Figure 2. (a) Counter map of the Nigorikawa caldera (after Kurozumi and Doi, 1994), and (b) subsurface geological structure of the Mori geothermal reservoir (after Kurozumi and Doi, 1993).

zone, which is located in the depth interval from 650 to 1,100 m MD (-500 to -990 m ASL), in the pre-Tertiary formation. The representative reservoir temperatures in the caldera wall and the pre-Tertiary formation are 240 and 200 °C, respectively. The produced brines are neutral to alkali and saline water, representatively containing 7.8–8.5 of pH, 350–650 mg/l of silica, 6,000–8,000 mg/l of chloride, 20–500 mg/l of sulfate, 40–120 mg/l of calcium and less than 6 mg/l of magnesium. The alkaline-earth elements constituting carbonate, sulfate and clay minerals, seem to be originated from limestone and marine rocks in the Kamiiso Group.

Various scale minerals, such as calcite ($CaCO_3$), anhydrite ($CaSO_4$), smectite (Mg-silicate) and calcium silicate hydrate, have been formed in production wells in the Mori field. Calcite deposit was first found to be a cause of serious decline in steam production in the beginning of the operation history. Mechanical workover operations revealed that calcite tends to deposit around a boiling depth. Hence, a scale inhibitor, a sodium polyacrylate solution, has been delivered through downhole tubing set several hundred meters below the boiling depth. Although the calcite scaling was inhibited with the solution, depositions of anhydrite and smectite were found to be another critical factor for production decline. We have controlled the anhydrite scaling with prevention and dissolution methods although smectite is still out of control. This paper reports our experiences in prevention and dissolution of the anhydrite deposit in production wells in the Mori geothermal field.

2. PREVENTION OF ANHYDRITE SCALING

A method to control of anhydrite scaling at the Mori field is injecting of a scale inhibitor, a sodium polyacrylate solution, into production wells. The inhibitor started to be applied first for calcite scaling in the early period of the power plant operation, and then its another ability to inhibit anhydrite precipitation was confirmed. This section describes how the anhydrite prevention system has been developed with the examples of three production wells, NF-10, ND-11, and NF-11.

2.1 Prevention of anhydrite scaling in NF-10

A production well NF-10 drilled down to 3,226 m MD started production with the injection of a scale inhibitor, a sodium polyacrylate solution, at a depth of 2,070 m MD for preventing calcite scaling in 1994 (Figures 3 and 4a). Injection of the polyacrylate solution has been successful in preventing calcite deposition not only for NF-10 but also for other production wells in the field.

NF-10, however, showed a significant decrease in the production in 1995 (Figure 3). A mechanical workover was conducted on the assumption that a scale deposit was blocking ascending of geothermal fluid from a depth. The workover revealed the scale deposition at the depth ranging from 2,317 to 2,530 m MD (Figure 4b), and mineralogical studies (e.g., X-ray diffraction analysis) on the returned scale samples indicated that anhydrite was dominant in the samples with a

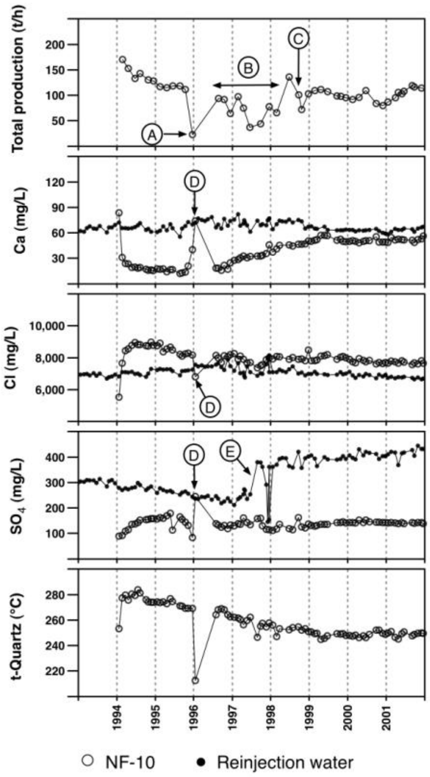

Figure 3. Histories of production and chemical composition of NF-10.

Open circle and solid circle represent NF-10 and reinjection water, respectively. [A] Decline in 1995. [B] Decline from 1996 to early 1998. [C] Production recovery in 1998. [D] Similar chemical composition of NF-12 brine and reinjection water during production decline. [E] Rise of sulfate concentration in reinjection water.

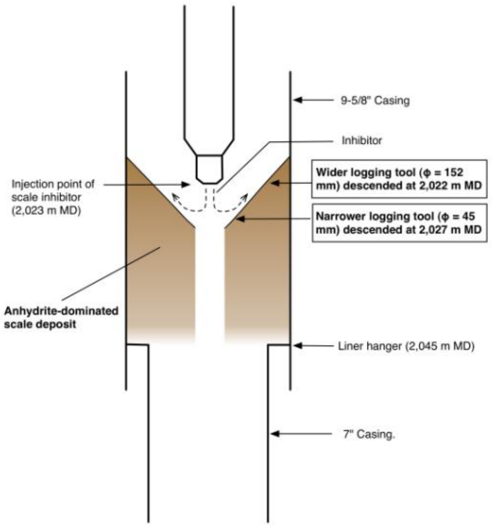

Figure 5. Estimated funnel-shaped top surface of scale deposit found in NF-10.

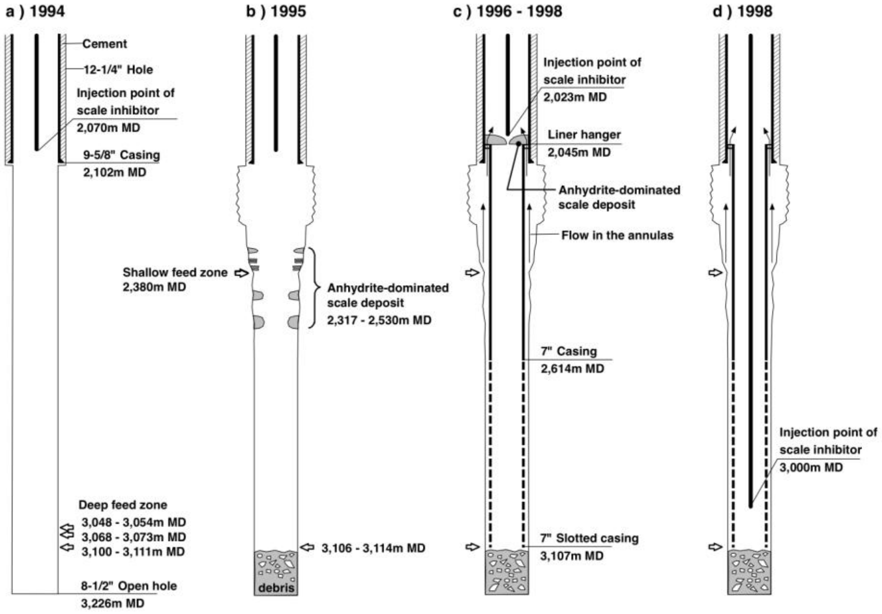

Figure 4. Locations of scale deposit and injection point of scale inhibitor in NF-10.

minor amounts of calcite and smectite. A flowmeter log taken after the workover unveiled a new shallower feed zone at 2,380 m MD in the section of the scale deposit, whereas only a deep feed zone had been observed at the depth ranging from 3,048 to 3,111 m MD in 1994 (Figure 4a). We concluded from these observations that the inflow of a water from the shallow feed zone induced anhydrite precipitation. For this reason, a 7-inch liner was set through the open hole section to cover the shallow feed zone (Figure 4c). The shallow water, however, could still flow upward in the annulus between the liner and the open hole, finally penetrating into the mainstream through aperture between the liner hanger (2,045 m MD) and 9-5/8-inch production casing (Figure 4c).

Although the liner setting could stopped the production decline for several months, NF-10 showed another decline and instability in the production from 1996 to early 1998 (Figure 3). Well logging in 1998 detected a scale plugging at the depth of the liner hanger just below the injection point of the scale inhibitor (Figure 4c). A mechanical workover was conducted after the logging, and anhydrite-dominated scale samples were sampled again. The results suggested that the shallow water penetrating at the liner hanger precipitated anhydrite.

Two logging tools having different diameters were used in the well logging, and the narrower tool (45 mm in diameter) descended deeper than the wider one (152 mm in diameter). We thought that the difference of the descending depth reflected a funnel-shaped top surface of the deposit as shown in Figure 5, and inferred that the inhibitor solution suppressed anhydrite formation at the surface center of the deposit. The injection point was therefore set at a greater depth of 3,000 m MD near the well bottom to prevent anhydrite scaling throughout the wellbore (Figure 4d). In consequence, as shown in Figure 3, the production recovered up to the level of 1995 to 1996, and has been stabilized to the present. Furthermore, no mechanical workover has been required for the well. The facts mean that the polyacrylate solution is highly effective for the preventing deposition of anhydrite as well as of calcite.

This method, in which the injection point of the scale inhibitor is set to a grater depth than shallow feed zone, has been applied on other production wells and provided good results as mentioned in the following sections.

2.2 Prevention of anhydrite scaling in ND-11

A production well ND-11 drilled up to 3,211 m MD started production in 1991 (Figures 6 and 7). ND-11 has a shallow feed zone at the depth ranging from 2,402 to 2,600 m MD and a deep feed zone at 3,069 m MD at the beginning of its production (Figure 7a). A polyacrylate solution has been injected since the start of the production to prevent calcite scaling. A scale deposit, however, was found at 2,445 m MD (Figure 7a) by well logging in 1993. Frequent fluctuations of wellhead pressure and a decline of the production were recorded between December 1993 and June 1994 (Figure 6). A subsequent mechanical workover revealed that the scale deposit and an expansion of the bore diameter occurred in the section between 2,442 and 2,573 m MD, which section corresponded to the shallow feed zone (Figure 7a). The scale deposit was a composite mainly of brecciated andesite of the formation rock and crystalline anhydrite with a small amount of calcite (Figure 8). In some parts of the deposit, fragments of the andesite were embedded in the crystalline anhydrite (Figure 8a), and automorphic anhydrite crystals were found in openings in the layered deposit (Figure 8c). The observations indicate that the formation (crystal growth) of the anhydrite was secondary and induced brecciation of the andesite formation rock and consequently expansion of the wellbore.

After removal of the scale deposit, a 7-inch liner was placed on the open hole section to avoid collapse of the wellbore in 1994, and the equal-sized slotted liner was used at both the shallow and deep feed zones (Figure 7b). The slotted liner allowed the shallow water to flow into the wellbore, and a well log revealed a penetration of water through aperture between the liner hanger (1,940 m MD) and 9-5/8-inch production casing. Although the workover increased the production once at least, a large production decline occurred around the beginning of 1996 as shown in Figure 6.

A mechanical workover was accordingly carried out again in 1999. A relatively thick scale deposit composed mainly of anhydrite was found in the section of the shallow feed zone (Figure 7b). We concluded from the observation that the penetration of the shallow water caused anhydrite deposition as in the case of the scaling in NF-10. The injection point of the inhibitor was accordingly placed below the shallow feed zone as shown in Figure 7c. This relocation of the injection point has been greatly contributing to the recovery and stability of the production of ND-11 after the middle of 1999 (Figure 6). An important thing learned from this case is that anhydrite has an ability not only to plug but also to collapse a wellbore.

2.3 Prevention of anhydrite scaling in NF-11

A production well NF-11 drilled up to 3,250 m MD started production in 1995 with an injection of a polyacrylate solution at 2,125 m MD (Figures 9 and 10). NF-11 has a shallow feed zone at the depth ranging from 2,550 to 2,620 m MD and a deep feed zone at the depth ranging from 2,950 to 3,208 m MD (Figure 10a). A 7-inch liner was set through the open hole section in the well completion, and both feed zones were covered with slotted liners, allowing waters to enter from each of the feed zones.

Because declines in wellhead pressure and production were observed in 1997 (Figure 9), a mechanical workover was conducted on the

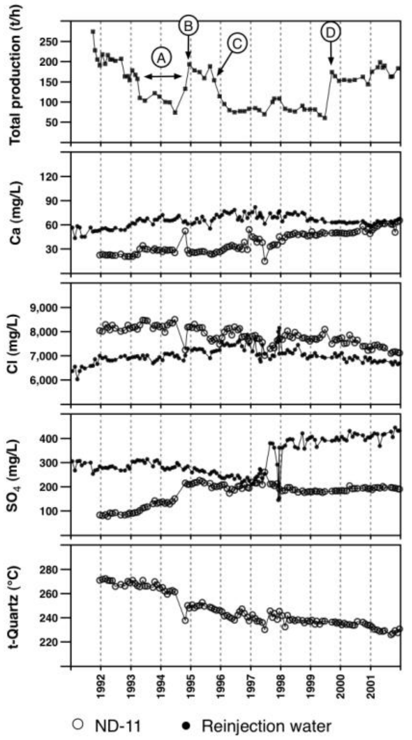

Figure 6. Histories of production and chemical composition of ND-11. Open circle and solid circle represent ND-11 and reinjection water, respectively. [A] Decline from 1993 to 1994. [B] Recovery after 7" liner setting. [C] Decline around 1996. [D] Recovery after lowering injection point of scale inhibitor.

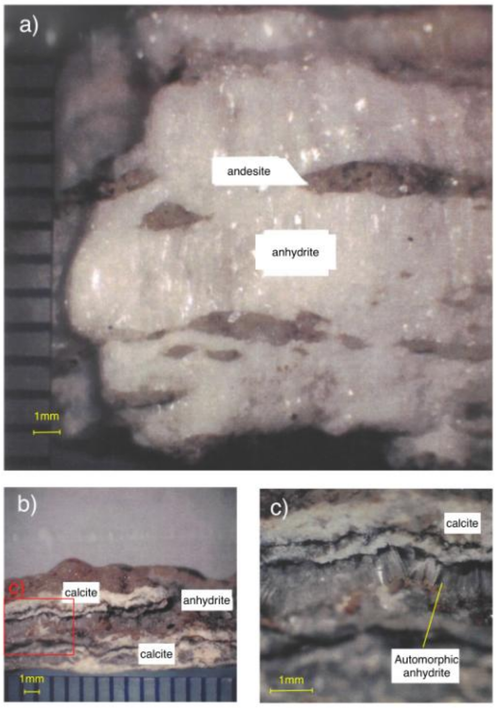

Figure 8. Scale samples composed of brecciated andesite and crystalline anhydrite recovered from ND-11. (a) Andesite fragments in crystalline andesite. (b) Layered scale sample composed of anhydrite and calcite. (c) Automorphic anhydrite formed in an opening in the layered scale sample of (b).

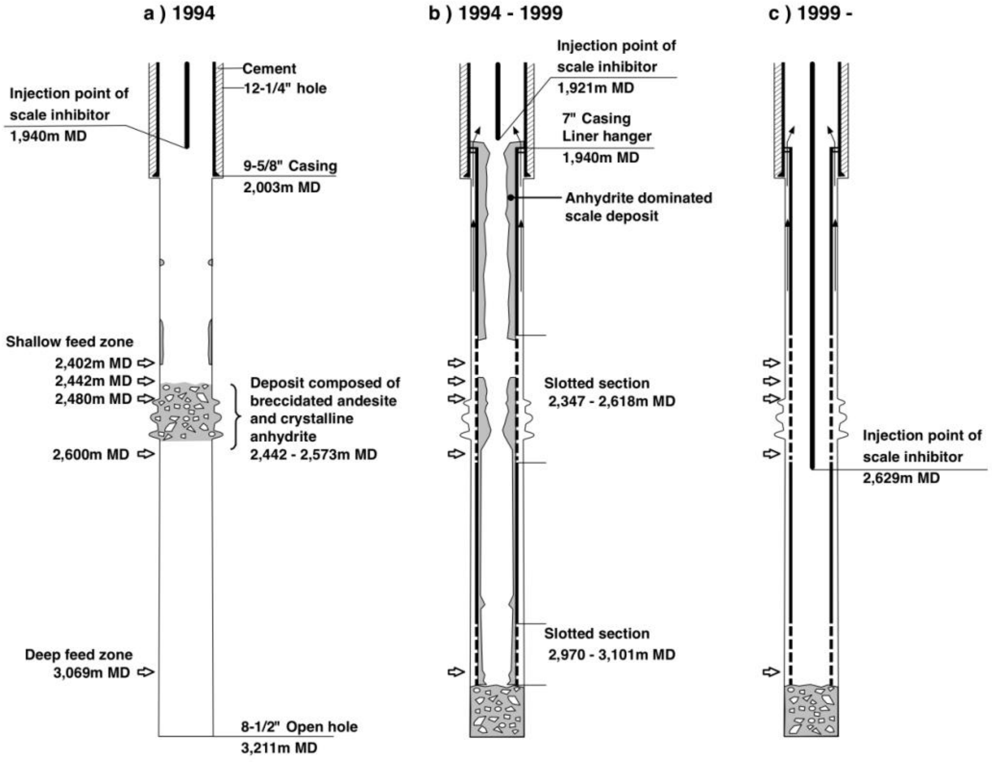

Figure 7. Locations of scale deposit and injection point of scale inhibitor in ND-11.

assumption that scale deposition had occurred in the wellbore. A scale deposit composed of anhydrite, calcite and smectite, was found in the interval between the liner hanger and the shallow feed zone. However, the injection point of the inhibitor was kept at the same position as that before the workover (Figure 10b) because the mechanism of anhydrite precipitation was not well evaluated at the time in 1997.

Although NF-11 started production again after the workover, the well immediately showed a production decline, and was finally disconnected from the gathering system for the power plant within about a month. An urgent mechanical workover was performed and the injection point was lowered close to the well bottom (Figure 10c). This relocation of the injection point led to the recovery and stability of the production (Figure 9) as observed for NF-10 and ND-11.

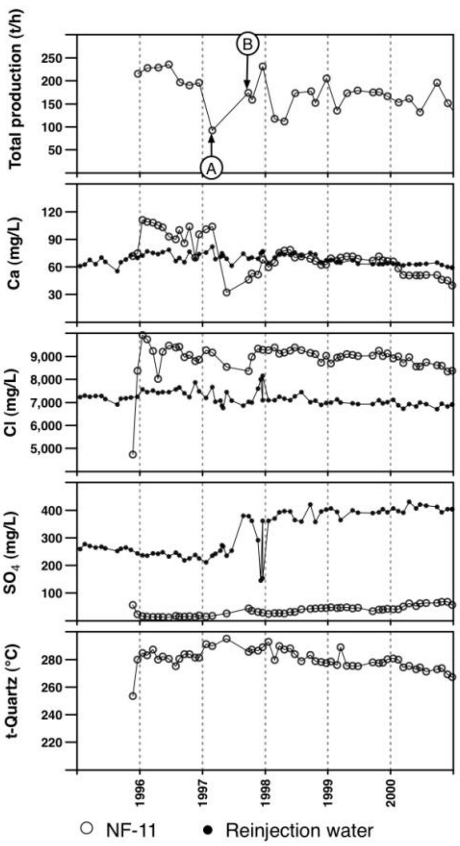

Figure 9. Histories of production and chemical composition of NF-11. Open circle and solid circle represent NF-11 and reinjection water, respectively. [A] Decline in 1997. [B] Recovery after lowering injection point of scale inhibitor.

3. GEOCHEMICAL MODELING OF ANHYDRITE PRECIPITATION

As previously mentioned, the shallow water in the wells NF-10, ND-11, and NF-11 is supposed to precipitate anhydrite. In this section, reinjection water is examined for the potential to precipitate anhydrite and to be an origin of the shallow water by geochemical modeling.

There are three reasons why the reinjection water can be regarded as a component of the shallow water as follows:

1) The reinjection wells are drilled in the shallow part of the Nigorikawa caldera, and the injection water flows downward to the production zone through the caldera wall (Figure 2b);

2) Strong hydraulic connectivities have been observed between the reinjection and production wells including NF-10, ND-11, NF-11, and NF-12 through a number of tracer tests (Watanabe et al., 2005) and monitoring of fluid geochemistry;

3) The chemical composition of the production water of NF-10 approached that of the reinjection water when only the shallow water was produced because the scale deposit was blocking the production from the deep feed zone in early 1996 (Figure 3).

Saturation index of the reinjection water for anhydrite was computed with temperatures from 125°C (actual reinjection temperature) to 300°C using computer programs SOLVEQ and CHILLER (Reed, 1998, 2006a, b). Figure 11 shows the anhydrite saturation indices of the reinjection waters sampled in 1994, 1995, 1998, and 2010, and demonstrates that the reinjection waters are supersaturated with the mineral over 235°C in 1994 and 1995, and over 205°C in 1998 and 2010. These temperatures are within the range of the reservoir temperature. Because another computation showed that production water alone has no tendency to precipitate the mineral, it is very likely that the reinjection water is an origin of the shallow water that has the potential to precipitate anhydrite. The trigger for the precipitation is heating of the reinjection (shallow) water, and the heat can be given by mixing with hotter deep water or by the hot reservoir rock.

The reinjection waters in 1998 and 2010 show higher saturation indices than those in 1994 and 1995 (Figure 11). This increase of the index is due to a rise of sulfate concentration in the reinjection water as seen in Figure 3, because sulfate is a constituent of anhydrite. The rise was induced by the injection of sulfuric acid into the brine line for prevention of silica scaling in the pipeline and reinjection wells. This means that the injection of sulfuric acid increases a risk of anhydrite scaling in and around production wells in the case where reinjection and production wells are strongly connected. The scale inhibition system in the Mori field has functioned effectively even under such a condition involving the strong tendency of the reinjection water to precipitate anhydrite.

4. DISSOLUTION OF ANHYDRITE DEPOSIT IN NF-12

A production well NF-12 was drilled down to 3,056 m MD and has a shallow feed zone at the depth of

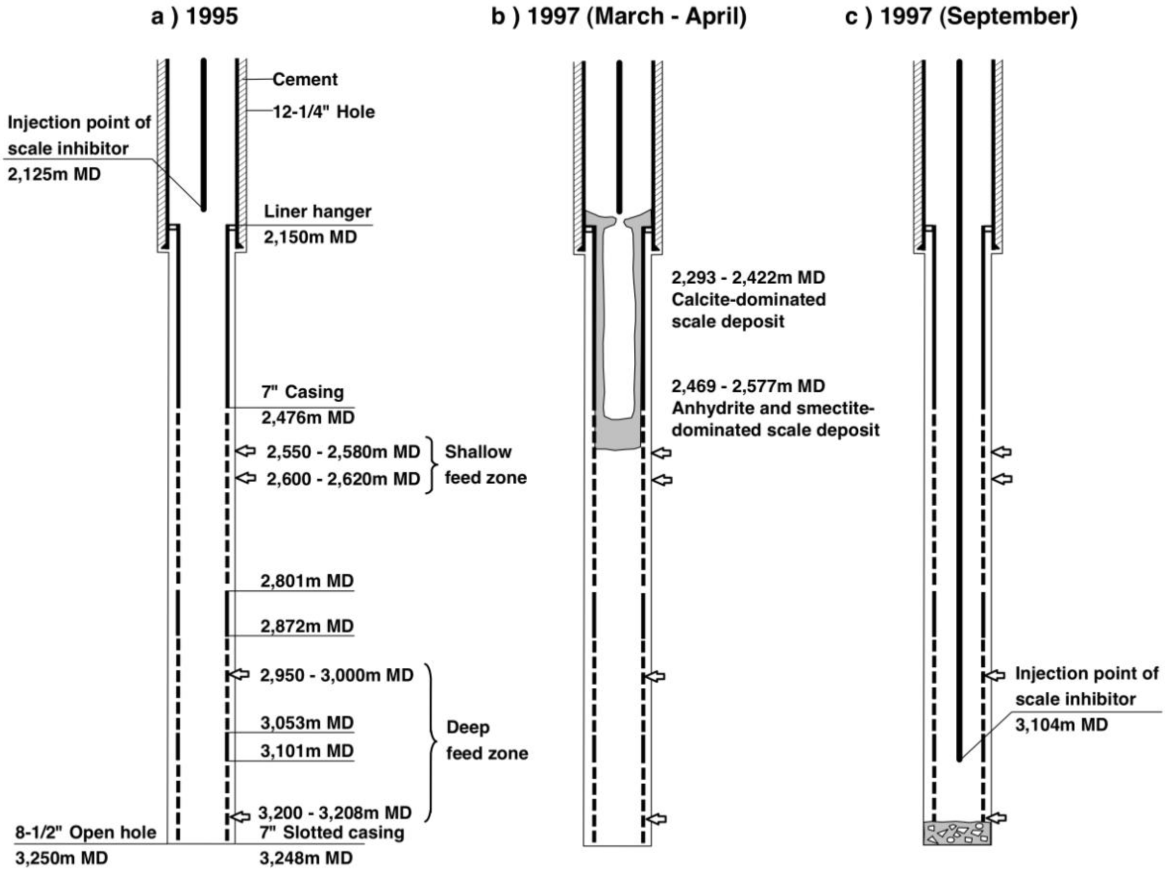

Figure 10. Locations of scale deposit and injection point of scale inhibitor in NF-11.

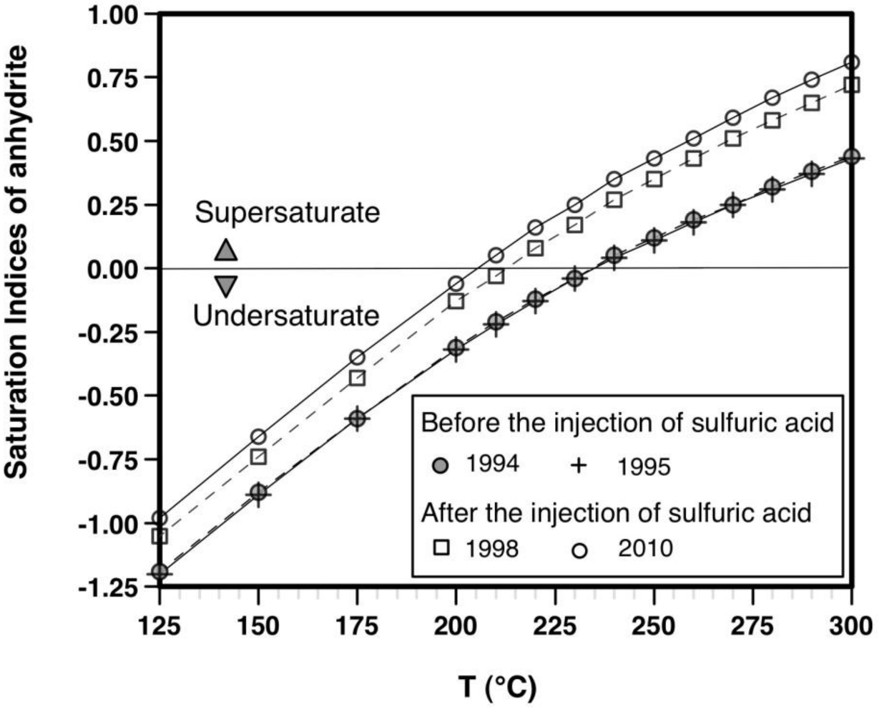

Figure 11. Saturation indices of reinjection waters in 1994, 1995, 1998 and 2010 for anhydrite.

2,110 m MD and a deep feed zone at the depth ranging from 2,788 to 2,964 m MD. The scale inhibitor had been injected since the beginning of the production.

In 2008 a well logging revealed that a scale deposit developed below the injection depth of the inhibitor. Anhydrite was assumed as the primary component of the deposit because anhydrite was identified in the solid residue of the brine by X-ray diffraction analysis, and in the neighboring production wells such as NF-10, ND-11, and NF-11. Experiences in the assessment of anhydrite deposition for the wells provided an image of scale deposition between the liner hanger and the injection point of the inhibitor in NF-12 (Figure 12a).

For scale removal from the wellbore, chemical dissolution was considered because it is less costly than a mechanical workover, and can be completed in a short time (Fukuda et al., 2010). We selected a chelating agent as a dissolving agent because it has an ability to dissolve sulfate minerals as confirmed in oil fields (e.g., Crabtree et al., 1999 and Moghadasi et al., 2007). Furthermore, Mella et al. (2006), Rose et al. (2007), and Nami et al. (2008) have studied well stimulation using chelating agents in EGS fields. Two kinds of chelating agents, ethylenediaminetetraacetic acid (EDTA) and nitrilotriacetic acid (NTA), have been tested in their studies, and we used a sodium salt of EDTA.

The operation of chemical dissolution for NF-12 was conducted from the 16th to the 20th of November 2008. The amount of the anhydrite scale was estimated to be 1,190 kg; therefore, 4,000 kg of the sodium salt of EDTA was prepared on the assumption that one mole of EDTA dissolves one mole of anhydrite (Bodine Jr. and Fellnard, 1973).

A EDTA solution of 0.5–1 wt% (ca. 0.011 mol/l - 0.022 mol/l) was created and NaOH was added to it in order to raise the pH to more than 12 because the chelating ability of EDTA solution increases with increasing pH (Fredd and Fogler, 1998). The EDTA solution was continuously injected at the rates of 5–20 kl/h, and totally 445 kl of the solution was used in the operation. We expected the continuous injection to create a flow on the surface of the scale deposit and to accelerate the spalling process as seen in an experiment in which the stirring of the dissolving agent was highly effective for the spalling of the scale samples.

The effect of the chemical dissolution was evaluated by a caliper log and monitoring of the wellhead pressure and production flowrates. As shown in Figure 12b, the caliper log revealed the dissolution of the scale deposit and the dissolved volume was calculated to be about 0.4 m^3, which volume is comparable to the predicted one.

Discharge from NF-12 was initiated on the 12th of December 2008. The wellhead pressure and production flowrates increased after the operation as shown in Figure 13. Comparisons between June and December showed that the wellhead pressure increased from 12.4 to 17.3 bar, and the flowrates of steam and water increased from 14 to 22 t/h and from 79 to 118 t/h, respectively. These results proved that the EDTA solution is highly effective for the dissolution (removal) of anhydrite deposit.

5. CONCLUSIONS AND FUTURE WORK

Deeply drilled production wells (NF-10, ND-11, and NF-11) in the Mori field experienced production decline caused by anhydrite scaling in the wellbores. The production wells have deep and shallow feed zones, and the anhydrite scaling occurred around the shallow feed zones. Well logging, mechanical workover, and mineralogical study of scale deposit indicated that the inflow of the shallow water induced anhydrite precipitation, and that a scale inhibitor, a polyacrylate solution, has the potential to prevent the precipitation of anhydrite as well as of calcite. For this reason, the injection point of the inhibitor solution was set to a depth below the shallow feed zone, which has been greatly contributing to the recovery and stability of the production for NF-10, ND-11, and NF-11.

For scale removal from the wellbore, chemical dissolution was employed. In the chemical dissolution, a chelating agent (a sodium salt of EDTA) was used to dissolve anhydrite deposit in NF-12. The EDTA solution of 0.5–1 wt% was continuously injected into the wellbore at the rates of 5–20 kl/h, and totally 445 kl of the solution was used. A caliper log displayed dissolution of the deposit, and wellhead pressure and production increased after the operation. These results proved that the EDTA solution is highly effective for the dissolution of anhydrite deposit.

Reinjection water is examined for the potential to precipitate anhydrite and to be an origin of the shallow water by geochemical modeling. The results showed that the reinjection water has the potential to precipitate anhydrite and can be an origin of the shallow water. The modeling also revealed that the increase of sulfate concentration in the reinjection water leads to the increase of degree of supersaturation for anhydrite. This means that injection of sulfuric acid into the pipeline can increase a risk of anhydrite scaling in production wells. The scale inhibition system in the Mori field has functioned effectively even under such a condition.

Although scaling of anhydrite and calcite are under control with the prevention and dissolution methods, precipitation of smectite (Mg-silicate) is still unsolved problem. The next and final target is to develop an inhibition system to treat scaling of smectite as well as anhydrite and calcite. As a first step, miniature experiments have been conducted on site to seek an inhibitor for all the calcium and magnesium minerals found in the Mori field since last year. In the experiments, particles of the scale minerals were created by mixing chemical agents with brine in the experimental pipes. Then, a chelating agent, EDTA, was added to the brine to

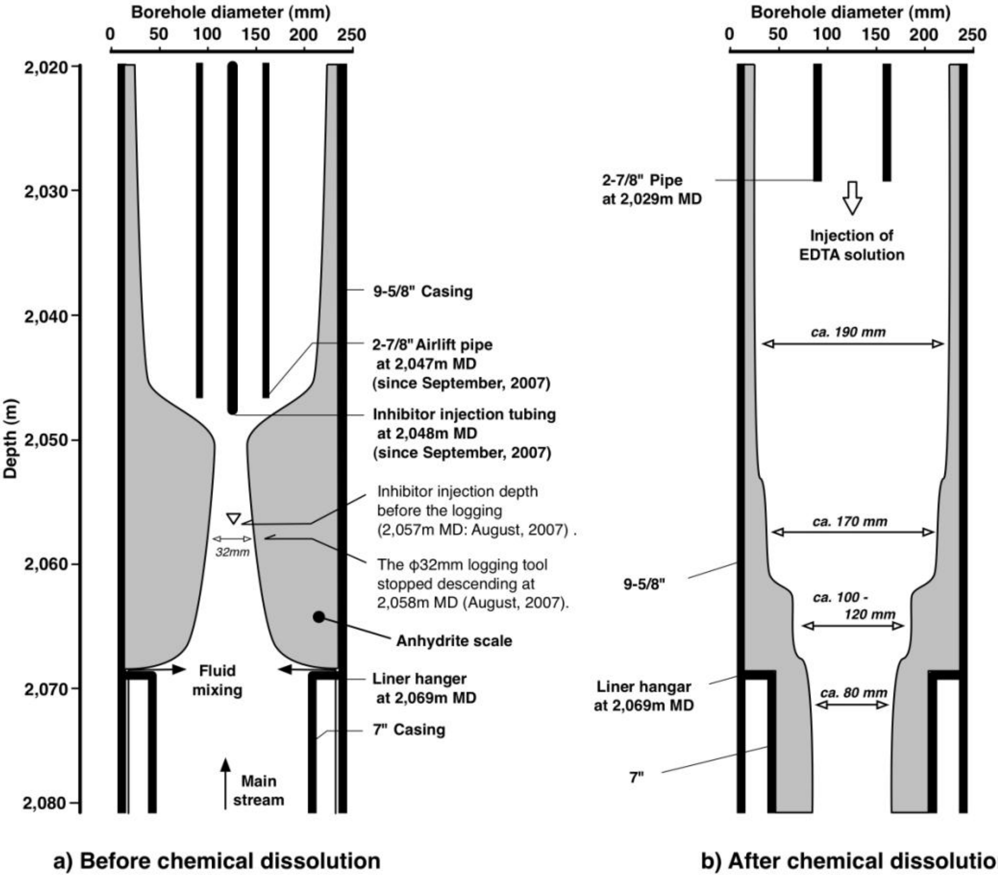

Figure 12. Anhydrite scale deposit in NF-12 before and after chemical dissolution. Wellbore diameter after chemical dissolution in (b) was measured by caliper logging.

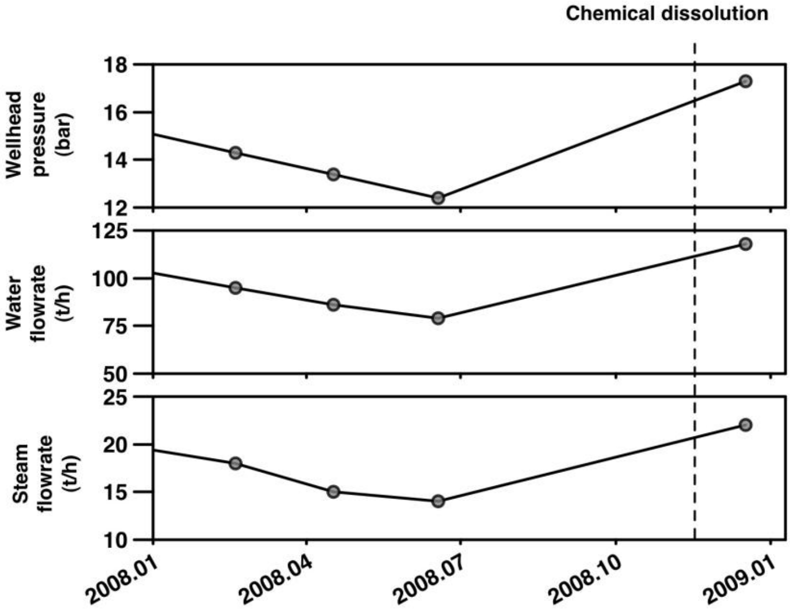

Figure 13. Histories of production and wellhead pressure of NF-12 before and after chemical dissolution.

prevent the formation of the particles. We have found that the chelating agent functions as an inhibitor for the calcium and magnesium minerals. This year, we will select the best one from candidates of chelating agents and optimize its use.

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