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The Role of Boron Cycling and Superheat Monitoring for Field Production and Injection Strategies at the Darajat Geothermal Field, Garut, Indonesia

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ABSTRACT

Boron is a conservative element that prefers to exist as a dissolved species in the liquid. One of the benefits of this particular chemical characteristic is that the migration of the liquid condensate injectate can be tracked through time.

The increasing trend of boron concentrations in produced steam and injectate at Darajat is hypothesized to be a result of efficient containment and re-injection of plant condensate back into the reservoir. From a geothermal reservoir perspective, the increasing trend of boron in steam represents a more active boiling of the condensate injected in the reservoir and it has increased the amount of condensate injection-derived steam. This steam contains increasing amount of boron as the re-injected condensed steam and accompanying boron are re-cycled.

This study describes boron cycling at the Darajat Reservoir, and correlation of bottom-hole superheat and produced non-condensable gas trends of some older wells at Darajat. It is suggested that condensate migrates away from injectors as liquid and partially boils concentrating the boron. Through time steam boiled from the more concentrated liquid injectate boils and increases the boron and decreases the non-condensable gas of the Darajat Reservoir. Another effect of the migration of partially boiled liquid injectate is that expected superheat increases are muted and delayed. This study will be used to help develop a 3D-conceptual reservoir model, to aid in the development of production and injection strategies for management of the Darajat Resource.

1. INTRODUCTION

Darajat is the largest producing vapor dominated geothermal field in Indonesia. It is located near Garut City, West Java Province, Indonesia about 150 km southeast of Jakarta (Figure 1). Darajat currently has 3 power plants (Units I/II/III) that generate a total of 260 MW of electricity to Java Island. Unit-I generates 55 MW and is operated by PT. Indonesia Power. Unit-II/III generates 95 MW and 110 MW, respectively, are operated by Chevron Geothermal Indonesia.

The exploration of this field started on 1984 and the generation of the electricity started in 1994. Currently, the Darajat field has 23 production wells that supply steam to the power plants, 4 injection wells, and 6 monitoring wells.

Boron re-cycling at Darajat is documented in this study and will used in the future to help manage injection and production strategies. A secondary use of this study will be to help constrain reservoir modeling to forecast production. Integration of both bottom-hole superheat and non-condensable gas production trends were used to help identify

Figure 1: Location of the Darajat geothermal field in relation to other cities in Java island.

and confirm the reservoir processes controlling boron systematics. In general, it is assumed that production of steam generated from boiling liquid condensate-injectate will lower both superheat levels and non-condensable gas (NCG) contents in the reservoir

2. PERTINENT BORON CHEMICAL CHARACTERISTIC.

Boron is a conservative element that prefers to exist as a dissolved species in the liquid. Equilibrium fractionation (i.e., log B value) of boron into the steam and liquid was first addressed in Glover (1988) and later incorporated in standard geochemical modeling software packages (e.g., SOLVEQ, Geochemist's WorkBench). The distribution of boron between vapor and liquid is described by the following equations in Glover (1988):

$$\frac{1}{K_D} = \frac{B_l}{B_v} 10^{[3.0506\text{-}0.00669t]} \text{, for 150-320}^oC \quad (1)$$

or

$$t\left({}^oC\right) = 456 + 149.5 \log K_D \quad (2)$$

where t, K_D, B_l, B_v are separation temperature, ratio of the boron concentration in the steam to that in the water, concentration of boron in liquid and concentration of boron in vapor, respectively.

For example at a reservoir temperature of 250^o C, the log B value of boron is -1.4 (or in other words, a liquid with 100 ppmw boron will generate a steam with ~ 4.0 ppm boron). With this theoretical background, the evolution of boron (B) in steam can give insight into the migration and boiling history of the condensate-injectate at the Darajat Geothermal Field.

3. DARAJAT FIELD BORON CYCLING

The source of boron in the Darajat Field comes from production well steam, condensate ports at the pipeline, plant mainstream header, cooling tower condensate, injection wells, and surface manifestations. Boron is analyzed from liquid samples collected at hot springs, condensate ports and injection wells. Production wells and fumarole steam are analyzed for boron by collecting samples using sampling probes/funnels and portable condensers.

Initial-state B in steam produced at Unit I was ~ 1.0 ppm in 1996. Currently in 2009, the average boron produced in Units I/II/III is 9.7 ppm. At initial-state conditions, B in steam was ~1.0 ppmw from the main production zone wells (center) and up to 7.2 ppm B in the shallow Condensation Cell (southern) wells. Figure 2 shows the 1995-1998 distribution map of boron at the Darajat Field.

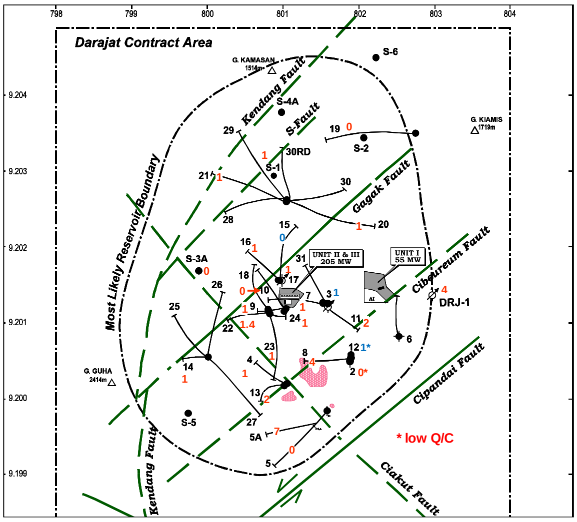

Figure 2: Darajat field 1995-1998 boron distribution map. Red values represent concentration of boron in production wells steam. The blue values represent concentration of boron in liquid injectate.

By injecting liquid condensate from the cooling tower into the reservoir, B in reservoir steam has progressively increased. B concentrations in liquid condensate injectate have increased from ~ 8 ppmw in 1996 to ~ 55 at end of 2008 (Figure 3). This marked increase is a result of the efficient containment and re-injection of cooling-tower liquid back into reservoir. DRJ-03 and DRJ-15 are the injection wells that are currently being used to inject B-enriched condensate continuously (Figure 4). B concentration of DRJ-03 injectate has increased significantly faster than DRJ-15 injectate. DRJ-03 supplies more B to the steam for two reasons: (1) the concentration in the injectate is higher and (2) its liquid is injected into the portion of the field with highest production rates and the longest period of extraction. Higher rates and prolonged production lowers the reservoir pressure and allows more boiling of liquid injectate.

By 2008, the highest concentration of boron (55 ppmw) in production steam was measured at DRJ-13 (Figure 3). Using a reservoir temperature of 250^{o} C, the fractionation between vapor and liquid is approximately 1/25 (refer to example in previous section). This suggests that the concentration of boron in the liquid injectate from which the DRJ-13 steam was boiled had a concentration of ~1375 ppmw. The applicability of this model presumes that liquid

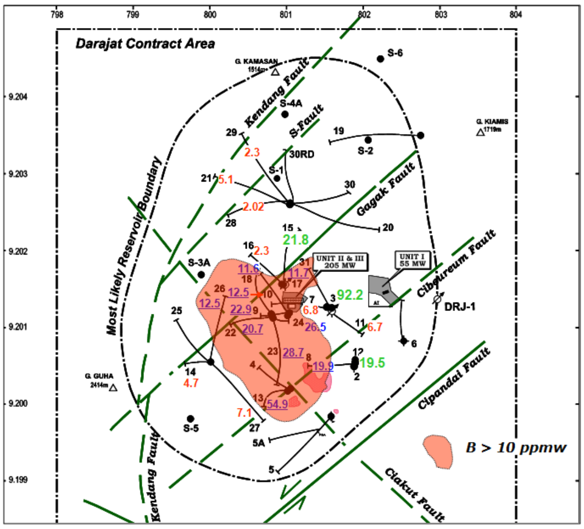

Figure 3: 2008 Boron distribution map of the Darajat Geothermal Field. Red values represent concentration of boron in steam <10 ppmw, while blue values are >10 ppmw. The green values represent concentration of boron in liquid injectate.

injectate is partially boiled as it migrates through the steam reservoir along fractures. A more detailed chemical discussion of the reservoir boiling model is presented in this volume in Mahagayo et al. (2010).

Assuming partial boiling of liquid condensate, it appears that concentrated liquid condensate liquid is migrating southeasterly to the shallow Condensation Cell production wells that are 2 km away from the nearest injector. This boiled liquid flashes and provides steam with concentrated B levels (>30 ppm B in steam) to production wells.

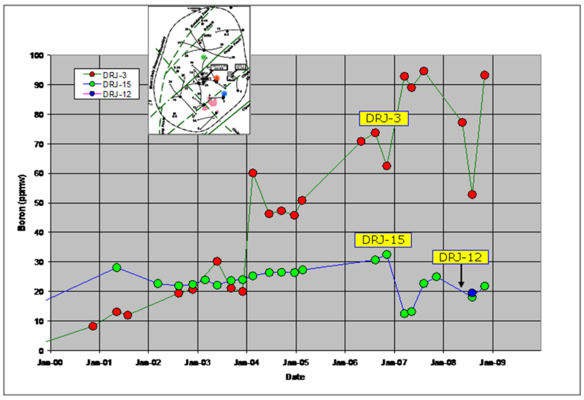

Figure 4: Historical boron concentrations in injectate for the Darajat Geothermal Field.

Monitoring of B in both fumarole steam and hot springs is performed annually to evaluate the impact of steam-generation at Darajat. In 2008, the natural steam measured at the Darajat fumaroles continued to contain very low concentrations of Boron (<0.3 ppm). In addition, the B concentration of the Darajat hot springs has not changed significantly since (pre-exploitation) records have been kept.

4. BORON PARTITIONING IN DARAJAT FIELD

The production wells, DRJ-08, DRJ-09, and DRJ-16 are selected to describe the boron-cycling in more detail. These wells were selected to represent different portions of the reservoir and depth of production. DRJ-08 has a large shallow entry and is located immediately east (possibly intersecting) the Cibeureum Fault. DRJ-09 has medium depth entries and is located 0.5 km east of the intersection of the Ciakut and Gagak Faults. DRJ-16 produces from deeper entries and all the entries are located in between of Gagak Fault and S-Fault.

4.1 DRJ-08 Production Well

DRJ-08 has been producing since 1995 and supplies steam to Unit-I. DRJ-03 is the closest continuously used injector to DRJ-08. Initially, this well had 0.3 ppmw of B and 2.2 wt. % of NCG. Figure 5 shows the history of B and NCG production in DRJ-08.

The B concentration of DRJ-08 increased significantly (3.5 ppmw/year) until 21 ppmw was reached in 2001. The NCG content decreased 0.5% weight in 12 years. Both chemical behaviors are consistent with the production of increasing amounts of steam from boiled injectate, probably originating from DRJ-03.

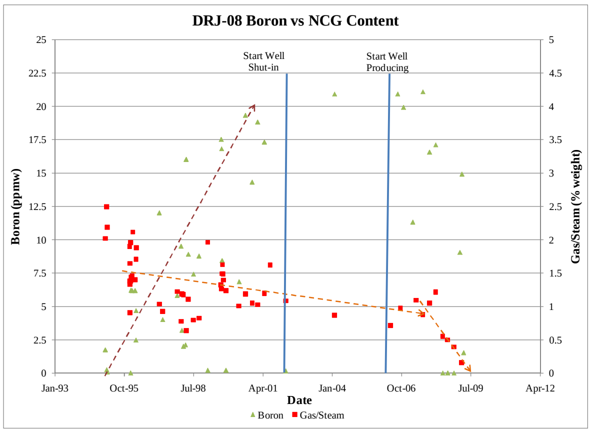

Figure 5: Time plot of boron vs NCG in DRJ-08.

Another possible impact of DRJ-03 injectate to DRJ-08 production may be that the superheat increase appears to be delayed until year 2006 (Figure 6). It is suggested that because DRJ-08 was operated at higher wellhead pressure (above 15 barg) before the well was shut in 2001 and the injected condensate from DRJ-03 was enough to keep the deeper entries of DRJ-08 at saturation.

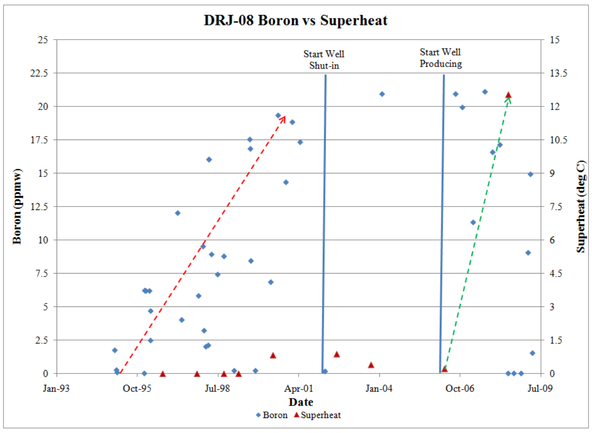

Figure 6: Time plot of boron vs superheat in DRJ-08

It appears that superheating on DRJ-08 may have begun in 2000, but was interrupted by shut-in conditions in 2001-02. However, at the end of 2006 after the well was re-opened, DRJ-08 deep entries started superheated significantly. The superheating was probably accentuated by the lower WHP (below 15 barg). In this case, the amount of injectate condensate that flowed to the DRJ-08 entries is not enough to maintain saturated conditions in the bottom hole. The superheating also causes more boiling of DRJ-03 injectate and any other liquid present.

4.2 DRJ-09 Production Well

DRJ-09 has been producing since 1995 and also supplies steam to the Unit-I power plant. Initially, this well had 0.4 ppmw of boron and 0.8 wt. % NCG. Figure 7 gives the history of B and NCG production in DRJ-09.

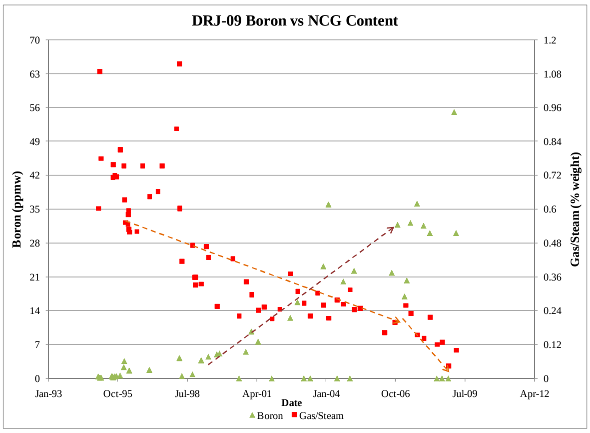

Figure 7: Time plot of boron vs NCG in DRJ-09.

DRJ-09 has a similar trend of B and NCG compared to DRJ-08. These trends are consistent with injectate from DRJ-03 also affecting DRJ-09. DRJ-09 has a slower rise in B and faster decline in NCG compared to DRJ-08. Both behaviors can be explained because DRJ-08 has a large shallow entry. This shallow entry allows more boiling (lower pressure) of injectate and is better connected to the shallow NCG-rich portion of the reservoir. The relative depths of the entries of DRJ-08 and DRJ-09 are shown in Table 1.

No	Feed Zones	Feed Zone Depth (m ASL)		
		DRJ-03	DRJ-08	DRJ-09
1	Feed Zone 1	720.00	997.51	663.27
2	Feed Zone 2	-	489.32	621.91
3	Feed Zone 3	-	385.20	596.55
4	Feed Zone 4	-	-	505.84

Table 1: Feed zone depth comparison among DRJ-03, DRJ-08, DRJ-09.

The more saturated conditions in DRJ-09, possibly maintained by injectate, would boil less injectate and slow the concentration of B in the liquid. The faster decline of NCG in DRJ-09 can be explained as more steam is produced from boiling injectate, before 2002. Continued operation of DRJ-09 at high wellhead pressure (above 15 barg) can explain the continued low superheat values shown in Figure 8.

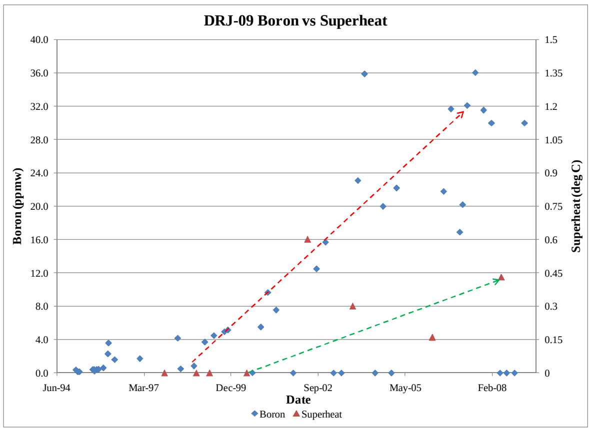

Figure 8: Time plot of boron vs NCG in DRJ-09.

4.3 DRJ-16 Production Well

DRJ-16 has been producing since 1999 and supplies steam to Unit-II/III plant. The location of DRJ-16 is closer to the DRJ-15 injection well than either DRJ-08 or DRJ-09. Initially, this well had 0.2 ppmw of B and 0.7 wt. % NCG. Figure 9 shows the history of B and NCG production in DRJ-16.

The B concentration of DRJ-16 steam has increased slowly (0.11 ppmw/year) while the NCG content in the steam was relatively stable before a "steep-drop" decline in 2007. Both extraction and injection increased in 2007 after Unit-III started-up. The steep increase in boron and decrease of NCG in DRJ-16 (Figure 9), since 2007, is consistent with the boiling of injectate and more production of steam generated from boiling injectate.

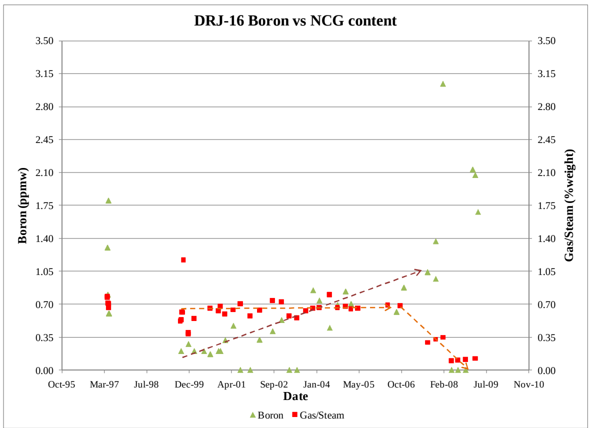

Figure 9: Time plot of boron vs NCG in DRJ-16.

The low B content of produced steam at DRJ-16 is caused by multiple factors: (1) the DRJ-15 injector contains lower boron (~20 ppmw) in liquid (Figure 3); (2) there are deeper exit entries for DRJ-15 injectate than DRJ-3, and (3) the later start-up times of production and injection north of Gagak Fault.

One main reason why DRJ-15 injectate may not affect DRJ-16 is that the feed zone depth of DRJ-15 is deeper than DRJ-16 as illustrated in Table 2. The low production of saturated steam from boiling injectate would allow the high superheats observed in the bottom of DRJ-16 (Figure 10).

No	Feed Zones	Feed Zone Depth (m ASL)	
		DRJ-15	DRJ-16
1	Feed Zone 1	133.10	697.05
2	Feed Zone 2	-308.20	586.92
3	Feed Zone 3	-	526.68
4	Feed Zone 4	-	417.25
5	Feed Zone 5	-	269.20
6	Feed Zone 6	-	249.75

Table 2: Feed zone depth comparison between DRJ-15 and DRJ-16.

Because of the small effect from DRJ-15 injectate, the bottom of DRJ-16 began to show superheat after only 2 years of production (Figure 10). By comparison, DRJ-08 and DRJ-09 showed bottom-hole superheats after at least 7 years of production (Figures 6 and 8, respectively).

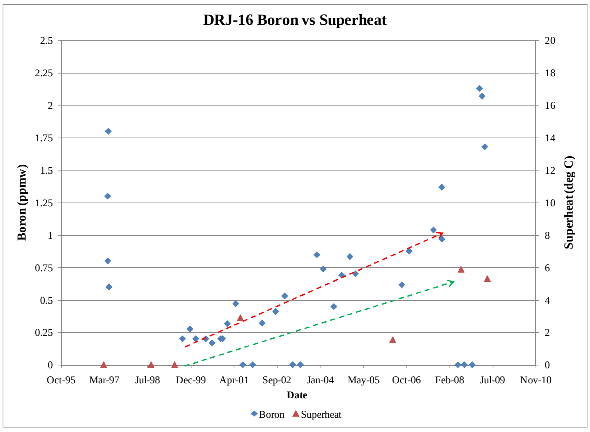

Figure 10: Time plot of boron vs NCG in DRJ-16.

5. SUMMARY

The boron cycling in production wells at Darajat is corroborated by historical NCG content. Trends in bottom-hole superheat data are more complicated. However, all of these data can be integrated and used as an effective tool to interpret the connectivity between injection wells and production wells.

The inverse relationship of lowering NCG content and increasing boron strongly suggests that the migration and subsequent partial boiling of liquid injectate has and will continue to occur in the Darajat reservoir.

Bottom-hole superheat trends appear to depends on the balance between the operating condition of production well and the amount of injected condensate that flows to the production well. High wellhead pressures and nearby liquid injectate has resulted in long term saturation conditions at the bottom of some production wells. In the future, superheat should continue to rise at Darajat with the added extraction of Unit III in 2007.

Finally, the relative positions of entries in injectors and producers can control the effects of injectate on individual wells. The injected condensate of DRJ-03 has a higher impact to the nearby production wells than the injectate of DRJ-15. In large part this is a result of DRJ-03 having a shallower exit zones than DRJ-15.

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