Natural State Chemistry of the Ijen Geothermal Field – A Blind Geothermal System

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ABSTRACT

In February 2025, Ijen Unit 1 achieved Commercial Operation Date with a declared capacity of 34.5 MWnet. The Ijen geothermal project is operated by Medco Cahaya Geothermal (MCG), as part of a joint venture (JV) between Medco Power International (MPI) and Ormat Technologies (ORA). The Ijen geothermal project is located in the Blawan-Ijen concession area, and the geothermal prospect that has been explored to-date is within Kawah Wurung area.

This paper will discuss the natural-state chemistry of the Ijen resource which is located within the Kendeng Caldera of the Ijen volcanic complex, situated in the eastern end of Java, Indonesia. Flow testing of wells during exploration and development drilling, plus early operational data, have been collated and analyzed. The flow testing and operational results support the existence of a two-phase, liquid dominated, >300°C resource with low total dissolved solids (TDS) (<0.3% Na-Cl fluid) and relatively low dissolved gas in the liquid phase.

1. INTRODUCTION

1.1 Project Location

The Ijen geothermal project is located in Ijen volcanic complex, Bondowoso Regency, East Java Province, about 40 km west of Banyuwangi city (Figure 1).

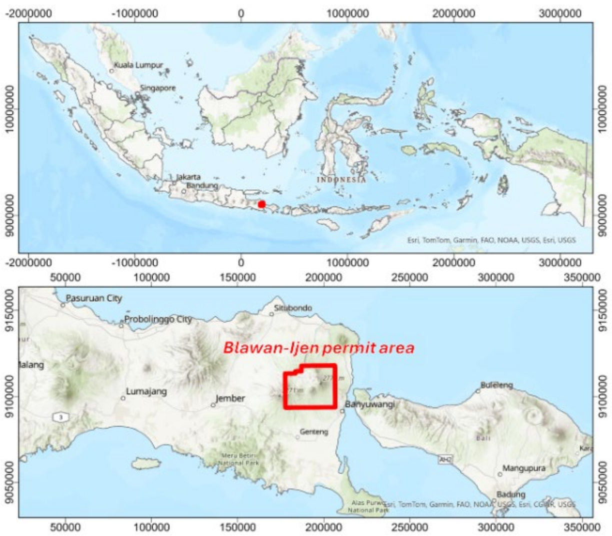

Figure 1: Project location of Ijen geothermal field.

The elevation of well pads ranges from 1,480 – 1,490 m relative to sea level (mrsl) (pads 1 and 9) to 1,520 – 1,590 mrsl (pads 2, 6, and 8). The average annual air temperature is 18.5°C in the project area, from data collected from an internal weather station installed near pad 6. It is 9.5°C lower than the average annual air temperature in Java (28°C) - a benefit for the efficiency of air-cooled condensers of the power plant.

1.2 Brief Project History

The first exploration of the Ijen geothermal project was conducted by PT Pertamina in the 1980-90s. It included the drilling of slim hole well ISH-01 to a depth of 620 m, which had a maximum temperature of 105°C. The project was obtained by MCG, a subsidiary of MPI, in 2011. New 3G datasets were later collected by domestic and international consultants (NewQuest and ELC) in 2012 and 2015 and a slim hole campaign was undertaken in 2016-2017 by a joint venture (JV) of MPI with Aboitiz Power. Two slim hole wells were drilled: IJN-1 was completed to the target depth (2000 m), however, the second well IJN-2 was terminated early at 775 m for budgetary reasons. IJN-1 confirmed high static temperatures (max recorded temperature of 289°C) and was able to flow steam. Aboitiz Power withdrew from the JV in 2017 while ORA joined MPI as a partner in 2019 by acquiring 49% of the shares of MCG from MPI. Additional geoscience investigations were undertaken and exploration plans were updated following the entry of ORA to the project. Exploration drilling was conducted in 2020-2021 with four large diameter wells (9.875 – 12.25” bottomhole diameters) targeting the Ijen resource, with one well being a reservoir side-track from one of the first three wells that were drilled.

Following the successful exploration campaign, the project was continued with development drilling of six wells in quarter two (Q2) 2023 to quarter one (Q1) 2024, consisting of four production wells and two reinjection wells. The drilling of full-size wells achieved a 90% success rate overall. EPC for construction, transmission line, and power plant was started in Q1 2023 and carried out in parallel with the development drilling campaign. The plant achieved commercial operation on the 7th February 2025 with a declared capacity of 34.5 MWnet, utilizing five production wells and one reinjection well.

2. SURFACE THERMAL MANIFESTATIONS

There are no surface thermal manifestations that are conspicuously related to the Ijen Resource. There are, however, warm springs discharging 6 to 8 km to NNE from the power plant (Figure 2). These springs are bicarbonate and sulfate (some trace of Cl) in character and have some component of acidic lake discharge from the Kawah Ijen crater lake that drains to the NW along the Banyupahit River (e.g., Delmelle and Bernard, 2000). However, their thermal character requires an additional larger component of hot, low-chloride water which could be steam-heated groundwater outflowing from Ijen geothermal system.

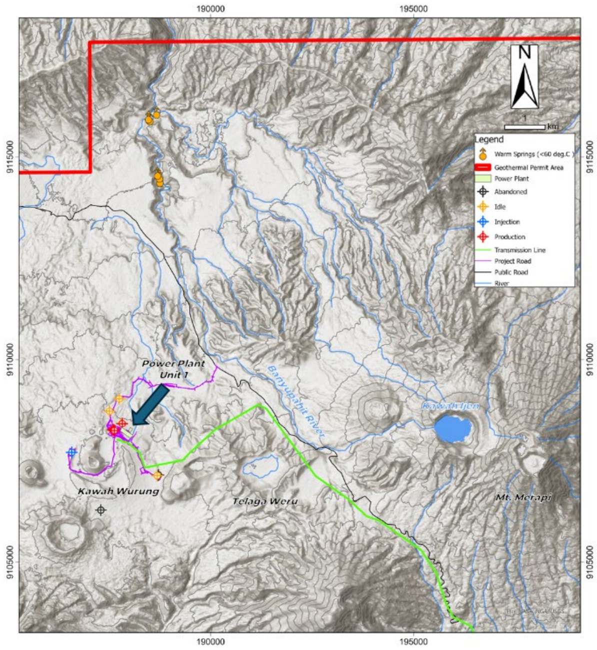

Figure 2 Summary map of Ijen geothermal project.

3. WELL CHEMISTRY CHARACTERISTICS

The slim hole well IJN-01 intersected the resource and was discharged for five days. Flow tests were conducted for 1 to 2+ month on eight of the large diameter wells. All wells were horizontally discharged into a silencer and the flow measured using the James's lip method (James, 1962) and Tracer Flow Test (TFT) was used for periodic well flow measurement and enthalpy determination to validate the James's lip readings. Complete chemistry of separated brine and steam was collected during the discharge tests.

3.1 Exploration Drilling Result

IJN-01 slim hole well was able to be flow tested and was sampled one year after well completion in June 2016. The well was logged 11 days after the completion of drilling with the highest static temperature of 289°C near total depth (TD) but the temperature profile collected is not believed to represent equilibrium conditions. The chemistry of this well showed excess enthalpy, with total discharge enthalpy (TDE) >2,200 kJ/kg and condensate-like HCO_3 chemistry with elevated B concentration (Figure 4 and Table 1) due to steam partitioning and condensation (Glover, 1988).

However, the liquid portion resulted to be in full equilibrium at ~240°C as suggested by quartz and Na-K-Ca geothermometers, with TDE > E(Na-K-Ca) = E(Qz) (Figure 3). This indicates that the condensate has been in contact with the formation at elevated temperature for long enough to approach the thermo-chemical equilibrium condition at the margin of the system as also supported by the near-neutral pH. An obstruction was identified in the well that prevented further downhole surveys and flow testing.

After ORA entered the MCG joint-venture, four large diameter wells were drilled, targeting the subsurface volume surrounding the Kawah Wurung Crater to test the conceptual model. Three of these wells were flow tested. The directions and location of the wells are shown in Figure 5.

IJN6-1ST was initially drilled as IJN6-1 and was the first complete large diameter well drilled to the target depth. Whilst drilling this well a severe steam-kick was encountered at a shallow depth (575 m measured depth or mMD) and the original leg (IJN6-1) was plugged and sidetracked as IJN6-1ST. This well is directional to the SW and encountered the highest measured temperature log during shut-in (PT-static) of 304°C at an elevation +300 mrsl followed by a strong reversal up to 178°C at TD (Figure 6). After 39 days of flow testing, this well proved a neutral-pH liquid-dominated reservoir exists, and over the flow test it showed signs of dilution seen from the decrease in Cl and an increase in SO_4, and HCO_3. Complexity in the chemistry interpretation was added as KCl was used in the reservoir section during drilling. A high SO_4 concentration (~385 mg/kg) is currently interpreted as a signature of marginal fluids originating to the west of the upflow. With TDE = 826 kJ/kg, the chemistry for IJN6-1ST also shows E(Na-K-Ca) > TDE = E(Chc) suggesting the possible mixing of primary reservoir liquid with cooler marginal recharge water (Truesdell et al., 1995).

IJN5-1 was the first well drilled directed to the east, however it resulted to be unproductive and was not flowed. Therefore, no chemistry interpretation of this well was undertaken.

IJN6-2 was the second well drilled directed to the east. Its T-static log shows a convective profile with a 20°C reversal near bottom of well. It was flowed for 75 days and chemistry confirmed the existence of the liquid dominated reservoir hosting near-neutral sodium-chloride (Na-Cl) type fluids with a TDS <2,000 mg/kg. The well exhibited cycling behavior during the flow test due to competing flow between steam and brine feedzones at depth as the liquid level reduced in the well over the duration of the flow test. Additionally, this well required a longer time to heat up and equilibrate as quartz geothermometry estimates of 300°C were confirmed by the temperature log in May 2023 with the highest measured temperature of 312°C. The overall enthalpy comparison, TDE = E(Na-K-Ca) = E(Qz), suggests that the well is located near the upflow.

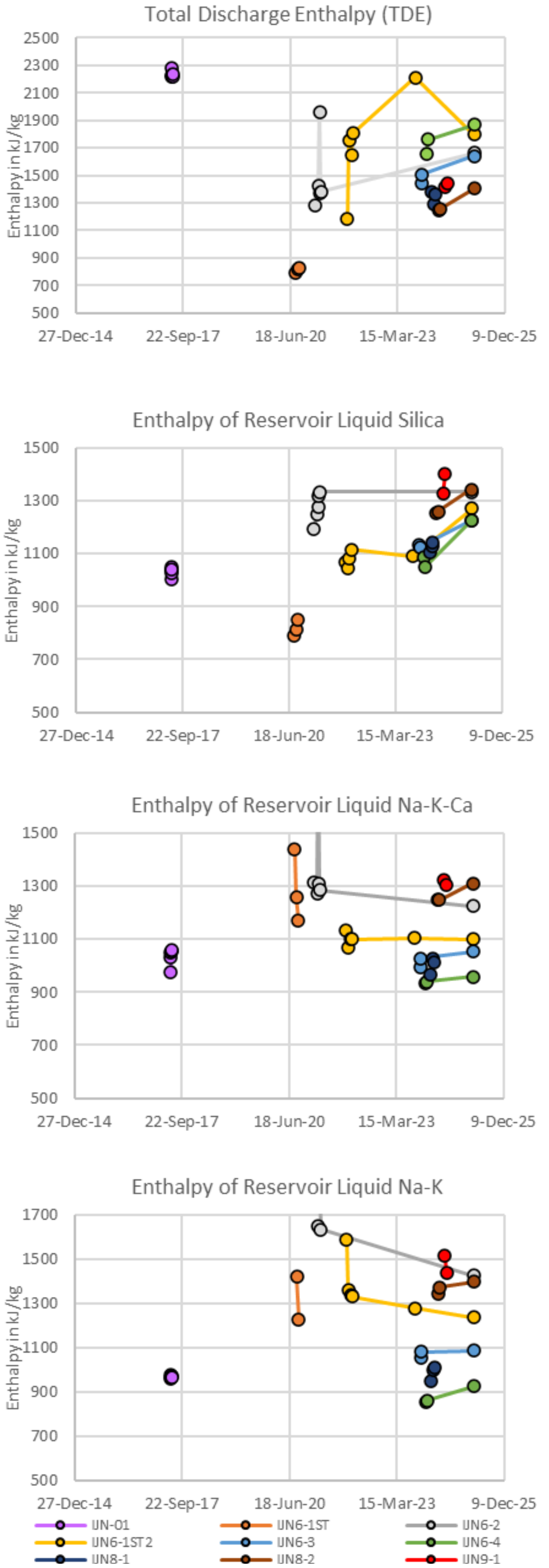

Figure 3: TDE and liquid enthalpy of different geothermometers calculated using the concentrations of reservoir liquid.

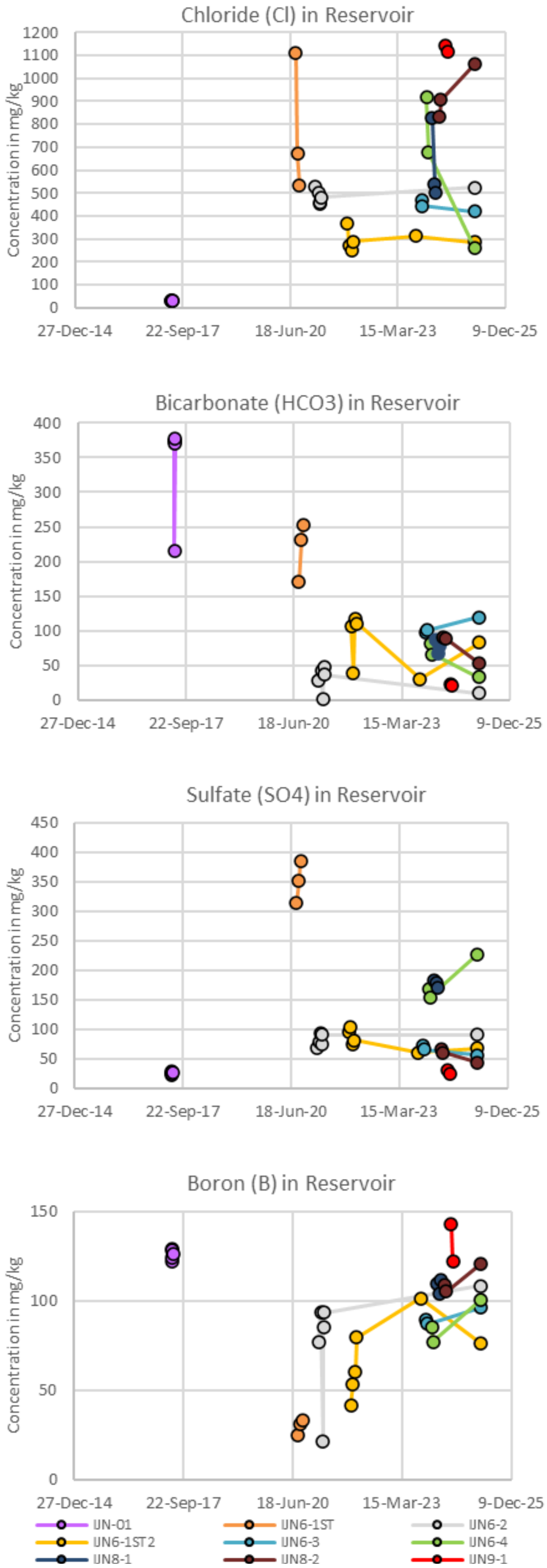

Figure 4: Concentrations of reservoir liquids calculated using the quartz geothermometer, except IJN6-1ST for which the chalcedony geothermometer was used.

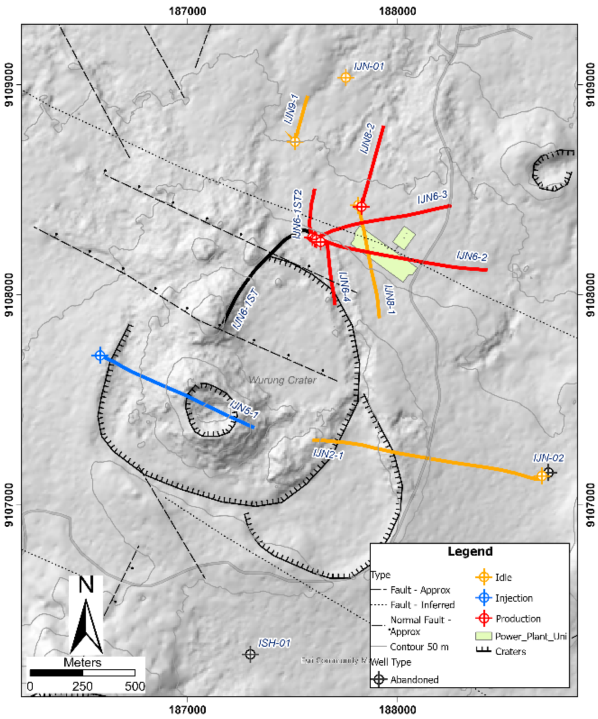

Figure 5: Map of well trajectories and types at Ijen geothermal project.

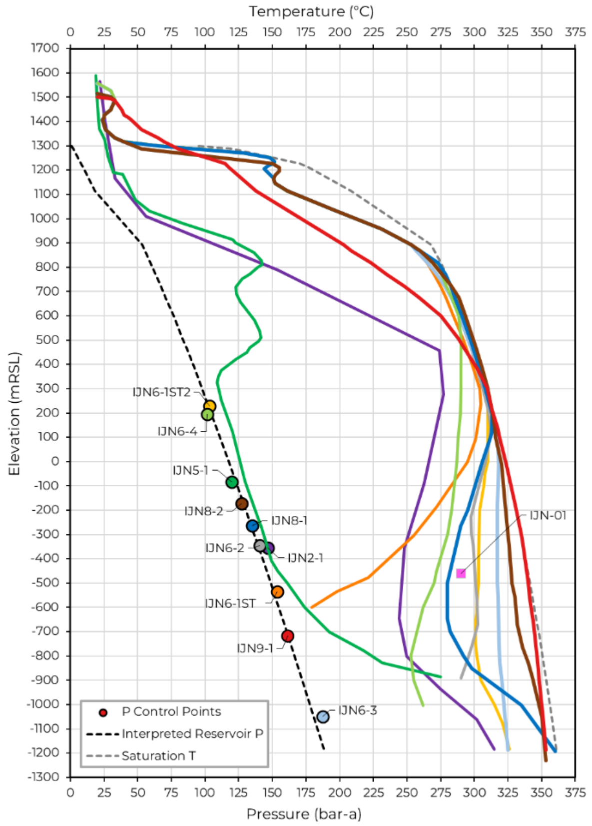

Figure 6: Interpreted natural-state temperature and pressure of Ijen wells (Libbey et al., 2026).

Following the testing of IJN6-1ST, the well was plugged and re-drilled to a northerly azimuth as IJN6-1ST2, and this was the last well drilled during the exploration campaign. This well was flowed for 2-months and was later re-flowed in 2023 for 35 days. Testing of this well further confirmed the existence of a neutral-pH reservoir fluid in the Ijen system. However, the reservoir fluids are more dilute compared to IJN6-2 in terms of Cl, Na, K and SiO_2. Some additional interesting findings are: (1) Na-K-Ca and quartz geothermometers are in agreement at 250°C while the TDE is 2210 kJ/kg resulting in TDE > E(Na-K-Ca) = E(Qz). (2) The T-flow log at the main feedzone is the same as the brine geothermometry value, ~250°C, in contrast to a T-static of 326°C at bottom-hole. Point (1) is the result of excess enthalpy from shallow feedzones in the two-phase region of the reservoir, while point (2) indicates that no notable permeability exists in the deepest/hottest regions of the well. The finding from point (1) also marks the potential marginal direction which is emphasized through T-static and T-flow log reversals at 250 m above the bottom of the well.

3.2 Development Drilling Result

The development drilling campaign at Ijen was conducted in 2023-2024. In this stage, six wells were drilled sequentially consisting of one injection well, IJN2-1, four productions wells, IJN6-3, 6-4, 8-1, and 8-2, and a future production/injection well to support resource performance, IJN9-1. These four production wells and IJN9-1 were flow-tested for 30, 43, 41, 44, and 45 days, respectively, according to the well drilling sequence. The simultaneous operation between flow testing and the drilling campaign was commenced to increase campaign efficiency and to inform future well drilling target decision making.

Three of the wells, IJN6-3, 6-4, and 8-1, display very similar characteristics to one another in terms of TDE and geothermometry. These wells have excess steam ranging from 14-40% and similar Na-K-Ca and quartz liquid enthalpies with TDE > E(Na-K-Ca) = E(Qz) (Table 1). This suggests that the brine comes from the deeper regions intersected by the wells and excess steam is contributed from the shallow feeds in the two-phase region of the system. The two-phase zone reaches temperatures >280°C in these wells, and there are temperature reversals near the base of the measured static profiles. These data support the notion that the shallow portion of these deviated wells penetrate through the upflow regions whereas their deeper portions begin to enter the margins of the resource.

IJN8-2 and IJN9-1 are drilled into the northern region of the system, towards the general subsurface location of the IJN-01 slim hole well. These wells encountered the highest chloride concentration in the reservoir section of the system (900 – 1,120 mg/kg) and there is agreement between the measured discharge enthalpies and brine geothermometers, with TDE = E(Na-K-Ca) = E(Qz). This suggests that these two wells are the most upflow-proximal and thus the most representative of the chemistry of the deep primary upflow fluid. This is especially true for IJN9-1, which has a quartz geothermometer temperature of 310°C and a maximum measured static temperature of 345°C at TD in August 2025.

Most of the wells have an unusual slow heat-up times that provides some challenges to the interpretations of the geothermal system and adds some uncertainty in the overall isotherm model of the system.

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4. RESERVOIR CHEMISTRY

4.1 Reservoir Characteristics

The static physical conditions alongside the flow testing results from the wells drilled and flowed to-date at Ijen geothermal system support the existence of a neutral Na-Cl geothermal reservoir which locally exhibits two-phase conditions in natural state. Conceptually, well chemistries at Ijen can be grouped into four end-member categories, as follows:

- ***Group 1: Main Reservoir** – IJN6-2, IJ8-2, IJN9-1*
  IJN9-1 has the most representative reservoir fluid found to-date and is located near to the upflow of the system with highest geothermometer temperatures recorded, ~310°C. IJN8-2 has concentration of several dissolved constituents (Cl, B, Na, K, Li, and SiO_2) similar to or moderately lower than of IJN9-1, yet geothermometer temperatures lower, 285°C. IJN6-2 shows some differences in composition, with almost half the concentrations of some dissolved constituents (Cl, Na, K, and Li) except B and SiO_2, the latter providing a quartz geothermometer temperature of ~300°C. It is inferred that the upper half of IJN6-2 penetrates into the main upflow region of the system, but its lower half may begin to enter the marginal regions.

- ***Group 2: Upflow Boundaries** – IJN6-1ST2, IJN6-3, IJN6-4, IJN8-1*
  Quartz and Na-K-Ca geothermometers provides temperatures of 240 to 260°C for these wells, indicating that these wells produce from lower-temperature feedzones at the margins of the system. These wells have high excess enthalpy because of contributions from shallow feeds in the two-phase zone, which is only distributed beneath pads 6 and 8 and not found below pads 2, 5 and 9. These wells have almost half the TDS and concentrations of dissolved constituents (Cl, Na, K, and Li) compared to Group 1 wells. Yet, they also have higher concentrations of species derived from marginal recharge fluids, such as HCO_3, SO_4, and NH_3, which are especially high in IJN6-4 and IJN8-1 (Figure 7).

- ***Group 3: Marginal Region** – IJN6-1ST*
  This well discharges a SO_4-rich fluid coming from shallow and comparatively cold feed zones situated in the northern side of Kawah Wurung. The sulfate source is still unknown, but may be related to the recycling of SO_4-rich steam-heated water back into the system. The use of sulfate isotopes may clarify this source in the future. In addition to the high SO_4 concentration, this well has lowest B, lowest silica geothermometer, and elevated Mg which is consistent with the influence of marginal fluids.

- ***Group 4: Steam Condensate on Margin** – IJN-01*
  This well produces a steam condensate which formed at northern the margin of the system and equilibrated with the reservoir rocks at around 240°C.

The B vs enthalpy plot provides a clearer picture on fluid characteristics and active processes in the Ijen geothermal system compared to the Cl vs enthalpy plot (Figure 8). Boron has the same conservative behavior as chloride and can be used to avoid potential misinterpretations of chemical data, in that chloride is influenced by drilling fluid contamination (Marini, 2022 and Libbey et al. 2022). This B-enthalpy diagram strengthens the interpretation that IJN9-1 is the most upflow-proximal well.

Table 1: Raw brine and gas chemistry data collected during flow-test activities from all production wells. Blank box is not analyzed. ATM = atmospheric. Chemical and TFT data of all well were collected using a small-size Webre separator except IJN6-1ST separated brines which were sampled at weirbox. Color label is that used in Figures 3, 4, 6, 8, 9, 10, 11, 12 and 13.

Well & Color Label	Date	Brine SP	Total Mass	TDE	Steam Frac.	Lab pH	Li	Na	K	Ca	Mg	SiO2	B	Cl	F	SO4	HCO3	NH3d
		barg	kg/s	kJ/kg	%		Concentration in mg/kg											
IJN-01	6/14/17	2.8	3.2	2232	76%	8.3	0.3	239	31	0.3	0.01	585	174	39		36	531	2.1
IJN6-1ST	9/13/20	ATM		826	19%	8.7	1.5	689	137	5.4	0.4	395	41	657	4.7	475	321	0.9
IJN6-2	4/2/21	5.3	39	1380	34%	7.0	1.4	462	141	5.3	0.03	969	136	703	10	132	66	1.8
IJN6-1ST2	8/29/23	7.3	35	2210	73%	5.9	1.1	307	66	4.7	0.01	592	128	396	7.6	76	144	2.4
IJN6-3	10/31/23	4.3	31	1508	41%	7.7	1.0	441	71	6.8	0.01	654	114	579	8.0	85	138	2.3
IJN6-4	12/22/23	4.7	32	1760	53%	6.9	1.2	673	72	7.7	0.01	545	97	848	13	193	108	2.4
IJN8-1	2/28/24	4.8	25	1366	33%	7.5	0.8	541	77	6.7	0.01	669	145	651	9.0	221	109	2.2
IJN8-2	4/19/24	6.0	52	1258	27%	7.7	2.7	786	188	6.2	0.01	843	145	1250	4.2	82	128	1.4
IJN9-1	6/19/24	3.2	28	1443	39%	6.9	6.6	1030	264	7.0	0.01	1100	190	1740	1.3	39	39	1.3

Well & Color Label	Isotope				Gas Chemistry															
	Brine d2H	Steam d2H	Brine d18O	Steam d18O	CO2	H2S	NH3	Ar	H2	CH4	N2	Gas in Steam	Gas in Total Flow	TDE	NKC Final	Qtz Final	%exc Steam	Geotherm. NKC Final	Geotherm. Qtz	Individual Well Geoindicators
	‰				Concentration in mmol/100mol H2O							Wt %		kJ/kg			in Qtz	deg. C		
IJN-01	-33.0	-46.4	0.2	-3.3	1020	63	1.9	0.05	14	2.7	4.8	2.6%	2.1%	2232	1059	1042	68%	244	241	TDE > NKC = SiO2
IJN6-1ST														826	1171	925	0%	267	216	NKC > SiO2 > TD
IJN6-2	-41.6	-50.2	-1.4	-4.5	838	68	1.3	0.07	0.9	1.2	5.6	2.1%	0.7%	1380	1286	1333	4%	289	298	TDE = NKC = SiO2
IJN6-1ST2	-38.9	-45.8	-1.1	-3.9	619	49	2.1	0.03	2.0	0.8	2.9	1.6%	1.2%	2210	1103	1089	65%	254	251	TDE > NKC = SiO2
IJN6-3	-38.5	-47.7	-1.3	-4.3	775	79	2.3	0.05	2.1	1.2	3.6	2.0%	0.8%	1508	1028	1124	23%	238	258	TDE > NKC = SiO2
IJN6-4	-37.7	-46.2	-1.3	-4.2	748	59	2.5	0.03	1.3	1.1	1.7	1.9%	1.0%	1760	941	1052	40%	219	243	TDE > NKC = SiO2
IJN8-1	-41.0	-49.5	-1.9	-4.9	655	39	3.0	0.09	1.3	0.9	2.6	1.7%	0.5%	1366	1013	1142	14%	235	261	TDE > NKC = SiO2
IJN8-2	-43.0	-49.3	-2.4	-5.3	478	21	1.7	0.20	1.0	0.8	16	1.2%	0.3%	1258	1248	1259	0%	282	284	TDE = NKC = SiO2
IJN9-1	-39.2	-51.1	-1.9	-5.2	312	22	0.7	0.12	2.0	0.5	10	0.8%	0.3%	1443	1303	1401	5%	292	310	TDE = NKC = SiO2

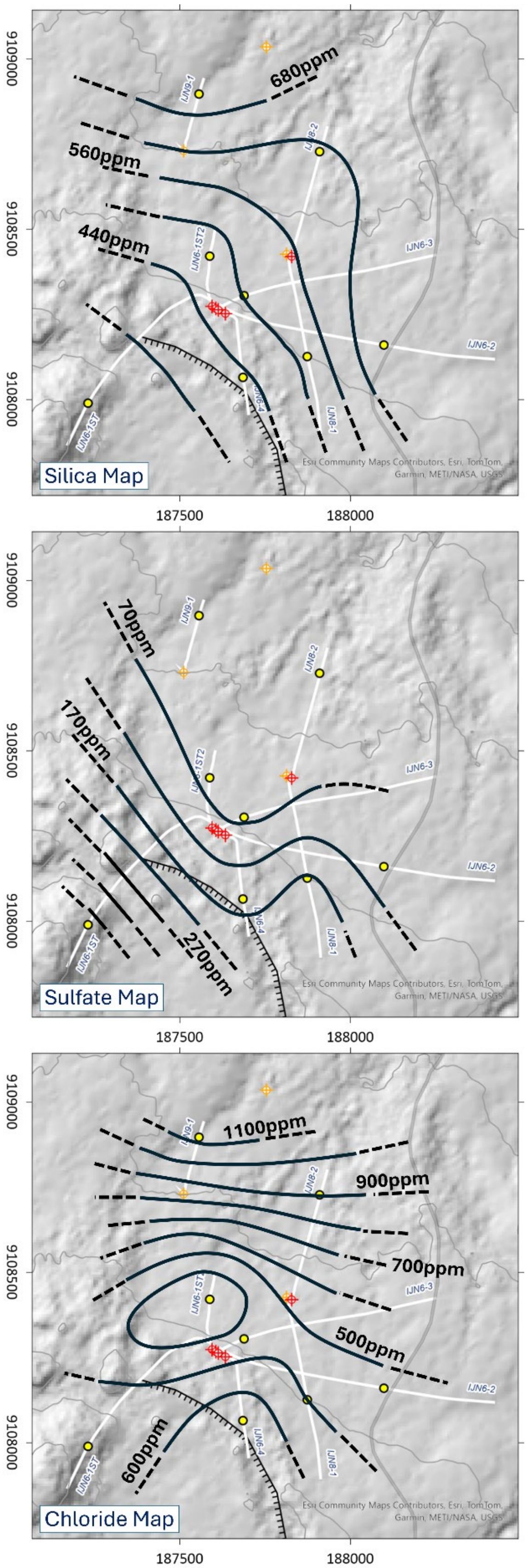

Figure 7: Iso-concentration maps of SiO_2, SO_4, and Cl in reservoir liquids. The pivot depth (yellow dot) on the well leg is the weighted average depth of feed zones. Dashed contour lines are interpreted.

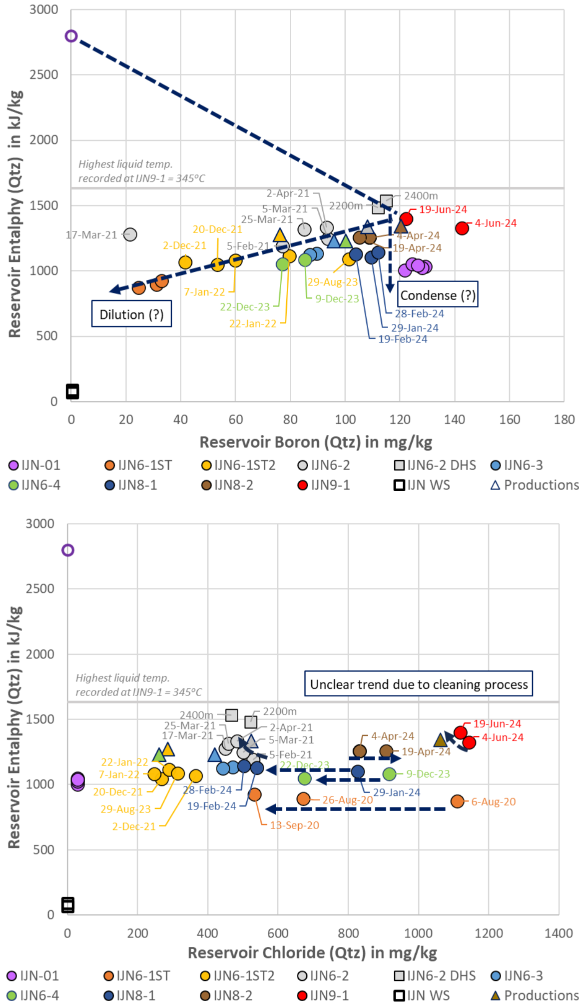

Figure 8: Comparison between B-enthalpy and Cl-enthalpy diagrams as reservoir liquid (based on quartz geothermometer). Labels represent the sampling date. Circles refer to reservoir liquids reconstructed from surface samples during flow test, squares refer to down hole samples (DHS), while triangle is the production data 3 weeks after COD.

The quartz geothermometer was evaluated to be the most appropriate geothermometer. The cation geothermometers may be somewhat affected by: (1) the use of KCl and KOH in the drilling fluids while drilling parts of the reservoir section, especially at exploration stage, as clearly seen in IJN6-1ST, and (2) calcite deposition, which was likely occurring during the flow tests.

The sulfate iso-map and B-SO_4 bivariate plot (Figure 9) provide support for the influence of pronounced marginal recharge in the southwestern and southern part of field (i.e., IJN6-1ST, IJN6-4, and IJN8-1). The ternary Cl-SO_4-HCO_3 diagram also supports this field-wide pattern and corroborates the notion that fluid samples from IJN-01 represent a condensate formed at the northern margins of a 2-phase reservoir.

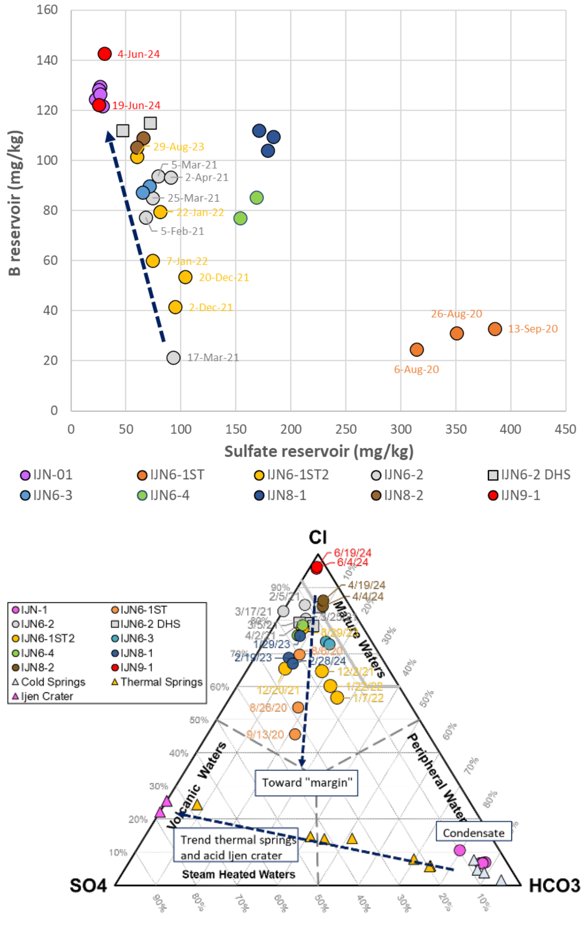

Figure 9: B-SO_4 bivariate plot (above) and Cl-SO_4-HCO_3 ternary diagram (below).

At present there are no clear acidity concerns in the natural state condition. Nevertheless, the field does have two-phase conditions, which provide the possibility for gas dissolution into shallow groundwater and the generation of carbonic and sulfuric acid conditions (upon O_2-driven H_2S oxidation), as seen in many fields, e.g. Rotokawa (Winick et al., 2011). They also provide the possibility for steam condensation to occur, with the steam condensate which may be of low pH. The elevated sulfate concentration of IJN6-1ST could pose some risk for anhydrite scaling if this marginal fluid is drawn into the production zone of the reservoir - a phenomenon that will be monitored through a rigorous chemical sampling program. There is no geological or conceptual support for the existence of an acid-vapor core associated with the Ijen system nor of the connection with the acid-vapor core system of the Kawah Ijen crater, which is located approximately 10 km to the east of the Ijen resource.

Gas concentration from all flow-tested wells ranges from 0.8 to 2.6 wt% NCG in steam. The wide range of gas concentration is related to the amount of shallow two-phase zone steam contributing to the total well discharge, in line with the spread of sample points in the N_2-CO_2-Ar ternary diagram (Figure 10). The varying contribution of two-phase feed zones is also apparent in the CAR-HAR and CO_2 vs enthalpy diagrams (Figure 10).

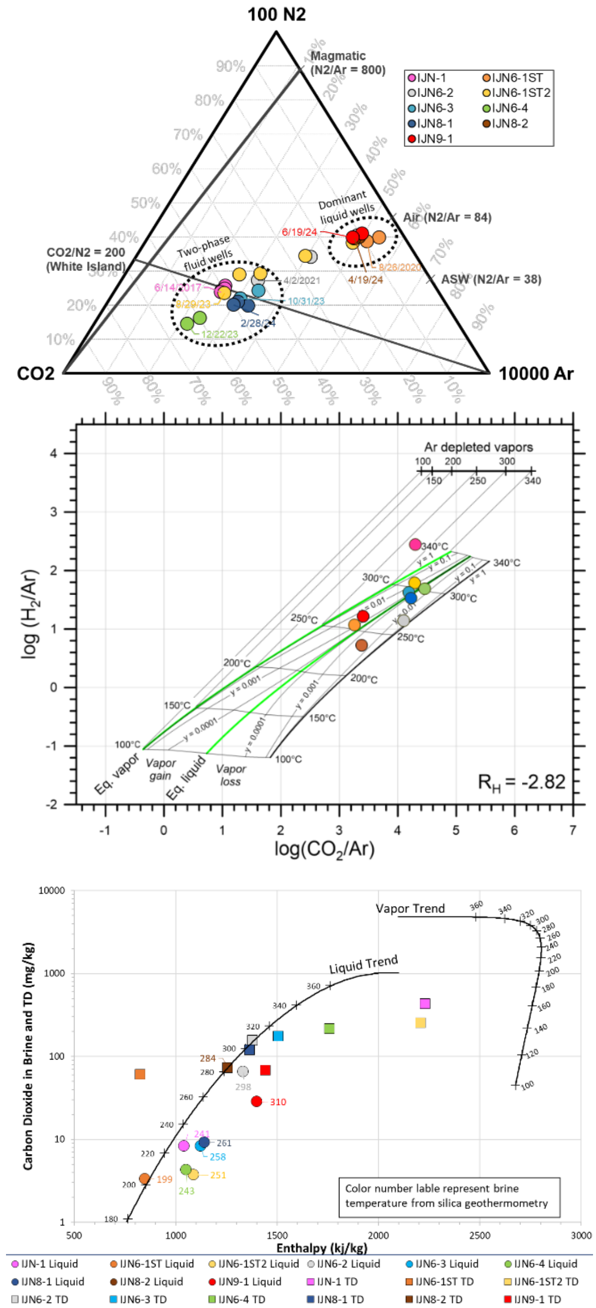

Figure 10: N_2-CO_2-Ar ternary diagram (uppermost), CAR-HAR diagram (middle), and CO_2 vs enthalpy diagram (bottom) show the gas characteristics of each well and two-phase fluid origin.

Each diagram shows good agreement with the concept of a high-temperature two-phase fluid (~300°C) based on the following hypotheses:

[I] The CAR-HAR diagram illustrates that gas species equilibrate in the liquid phase with limited gain/loss of equilibrium vapor (sensu Giggenbach, 1980), apart from IJN-01 which is the only well affected by addition of Ar-depleted vapor. This may imply (a) the wells are still under the impact of Ar-rich drilling fluids, or (b) it is a young (recently formed) two-phase zone.

[II] The implication of point (b) is supported by the CO_2-enthalpy diagram, in which the liquid line is defined by the geothermometric function of Arnórsson and Gunnlaugsson (1985) and the vapor line is constrained by the geothermometric function of Arnórsson and Gunnlaugsson (1985) and the vapor-liquid partitioning relation of Giggenbach (1980). The potential origin of the two-phase fluid is from a liquid phase in equilibrium with pertinent minerals at 300-310°C and the subsequent boiling process of this high-temperature liquid upon ascent.

The δD-δ[18]O total discharge diagram shows a positive oxygen shift which can be attributed to either addition of arc-type magmatic water (27 to 39%) to meteoric water or pronounced oxygen exchange during water-rock interaction or both (Figure 11). The only exception is IJN6-1ST, where the reservoir fluid has a higher percentage of local meteoric water. Based on chemical evidence (see above), the parental liquid is closely represented by IJN9-1, but the IJN9-1 reservoir liquid is isotopically lighter compared to other wells.

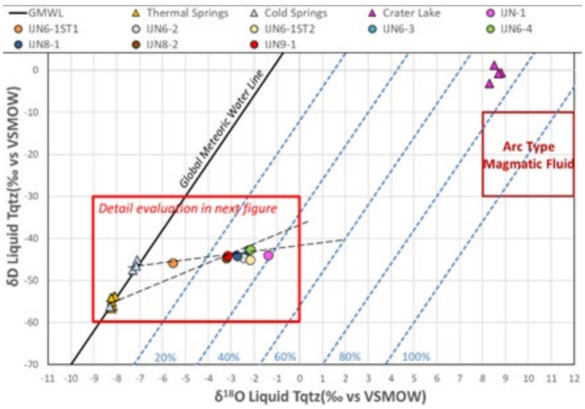

Figure 11: Water isotopes of all reservoir liquids based on quartz geothermometry.

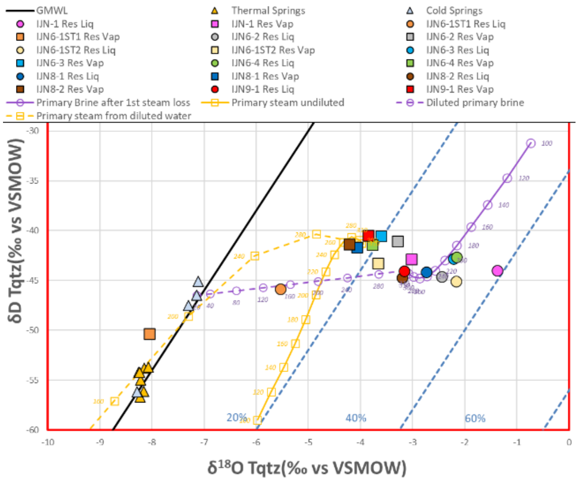

Figure 12: Water isotopes of all reservoir liquids and vapors and theoretical compositions for single-step steam separation from the undiluted and diluted parent liquid according to Giggenbach and Stewart (1982). Cold and thermal springs from Pasqua and Pisani (2012). Ijen crater lake data from Delmelle et al. (2000) and Lohr et al. (2007).

Figure 12 supports the occurrence of high-temperature vapor separation, as discussed in the gas analysis section, although there is some minor discrepancy, for both vapors and liquids, between observed compositions and theoretical compositions, calculated for single-step steam separation using the approach of Giggenbach and Stewart (1982).

Based on the isotopic data from cold springs, thermal springs and production wells, it is evident that magmatic fluids from the active Kawah Ijen crater do not impact the Ijen system (Figure 11).

5. RESERVOIR CHEMISTRY MODEL

The updated conceptual model following the development drilling campaign is shown as a map view in Figure 14 and 15. The fluid model process in the system is as follows.

[1-2] The main brine reservoir upflow of the Ijen geothermal system is characterized as a high-temperature resource >300°C, near-neutral pH, Na-Cl fluid with 2,500-2,850 mg/kg TDS, and a dissolved NCG concentration up to 0.8 wt%. The upflow of the system is interpreted to originate near IJN9-1 and extends to the southeast toward the subsurface regions intersected by IJN6-2. The evidence for this interpretation is given by Cl and B relationships (Figure 13), as well by other diagrams, such as B-enthalpy and Cl-enthalpy (Figure 8), and SO_4-B (Figure 9).

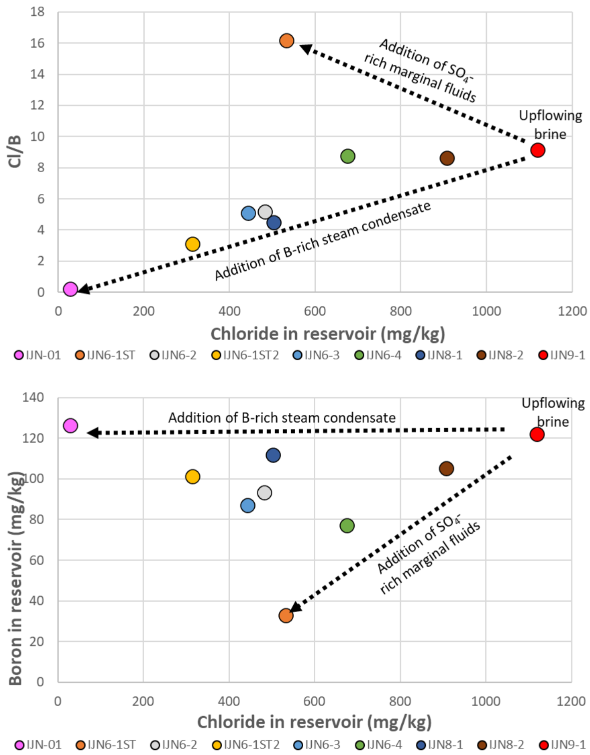

Figure 13: Bivariate plot of Cl/B ratio vs chloride (above) and Cl vs B (below).

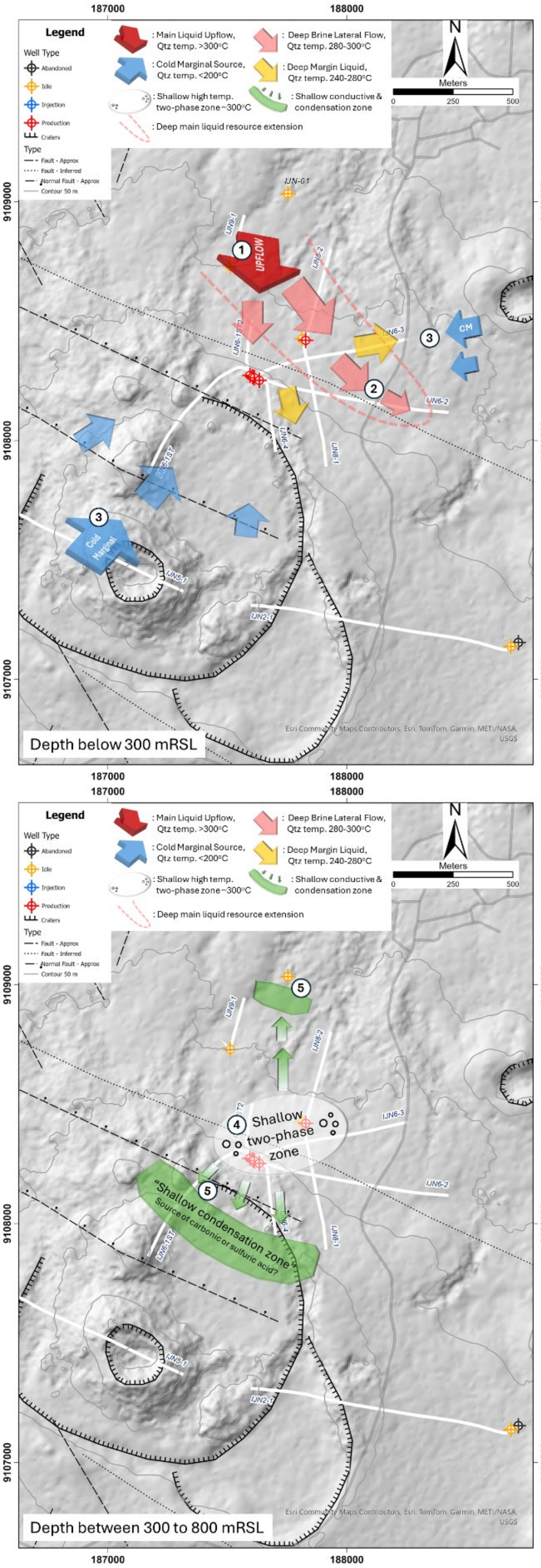

Figure 14: Detail map view of the Ijen geochemical model showing the path of distinct fluids at different depth. The map below +300 mrsl (above) depicts the brine flow paths and the cold marginal inflow while the map between +300 and +800 mrsl (below) show two-phase zone and the flow paths of steam condensate.

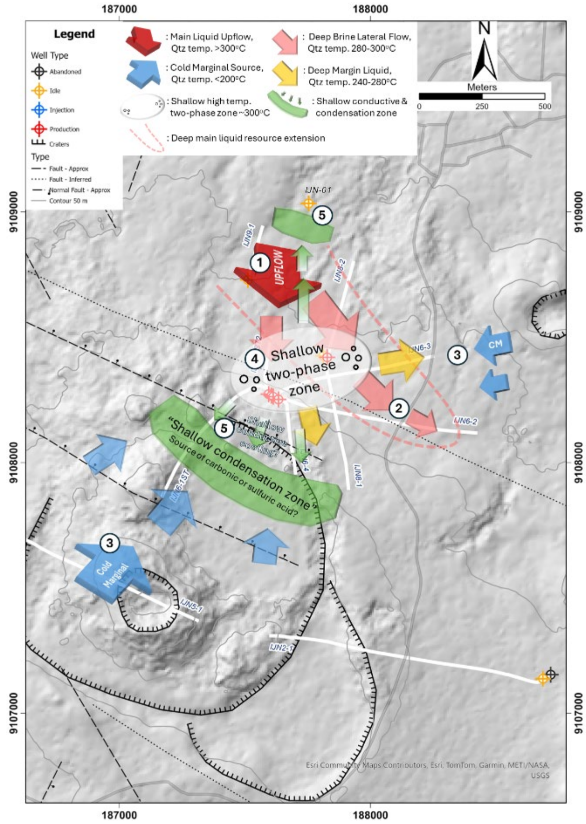

Figure 15: Map view of combined depth Ijen geochemistry model with workflow number 1 to 3 depicting condition below +300 mrsl, while number 4 and 5 depicting fluid flow between +300 to +800 mrsl.

[3] The extent of mixing with SO_4-rich marginal fluids or B-rich steam condensate increases with distance away from well IJN9-1, with decreasing Cl concentration resulting from both processes. These marginal wells IJN6-1ST2, 6-3, 6-4, and 8-1 have also lower equilibrium temperatures (~260°C) based on quartz and Na-K-Ca geothermometers. This colder marginal fluid has an elevated sulfate concentration, as seen in IJN6-1ST and, to lower extend, in 6-4 and 8-1.

[4] The two-phase region at Ijen exists in the subsurface region beneath pads 6 and 8 and does not extend much further to the north and south, based on data from wells drilled from pads 1, 2, 5 and 9.

[5] Steam condensate from this shallow high-temperature two-phase zone creates the potential for secondary fluids rich in carbonic acid and/or sulfuric acid on the margins of the system. This may explain the origin of sulfate and bicarbonate found in IJN6-1ST well to the southwest and the presence of bicarbonate- and boron-rich fluids re-equilibrated at temperatures of ~240°C in IJN-01.

However, the following uncertainties call for further evaluation during plant operations once the field is in continuous production:

(1) The possible origin of the sulfate-rich fluid present in the southwestern section of the system. The use of sulfate isotopes may assist in this analysis.

(2) Concrete explanation for IJN6-2 dissolved constituents of Cl, Na, K, and Li are by half compared to IJN9-1 and not SiO_2 concentration.

6. CONCLUSION

The Ijen geothermal system is a blind high-temperature system in the Sunda Volcanic Arc. The geochemical characteristics of brine and gas, including isotopes data, from the production wells, as well as measured in-hole PT data, provide a consistent pattern and allow one to update the conceptual model of the system.

Well fluid chemistry can be grouped into four end-member categories at Ijen, especially based on B-enthalpy and TD vs liquid enthalpy relationships above other chemistry analysis: (a) “main reservoir” found by the three liquid-enthalpy wells IJN9-1, IJN8-2 and IJN6-2 of which IJN9-1 is the most representative well intersecting the reservoir and also showing the highest temperature, as indicated by both chemical geothermometers and well T-log data; (b) “upflow boundaries” met by the excess enthalpy wells IJN6-1ST2, IJN6-3, IJN6-4 and IJN8-1, consisting of a shallow two-phase section followed by low TDS and lower temperature feedzones in the brine section (240-260°C); (c) “marginal region” encountered by IJN6-1ST as influenced by cooler sulfate-rich fluids from shallow sources; and (d) “marginal steam condensation region ” as found at IJN-01 whose fluids are affected by condensation and re-equilibration with reservoir rock at ~240°C.

Available isotopic data indicates that magmatic fluids from the active Kawah Ijen crater do not impact the Ijen system.

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REFERENCES

Arnórsson, S., Gunnlaugsson, E. (1985). New gas geothermometers for geothermal exploration—calibration and application. Geochimica et Cosmochimica Acta, 49(6), 1307-1325.

Delmelle, P., Bernard, A. (2000). Downstream composition changes of acidic volcanic waters discharged into the Banyupahit stream, Ijen caldera, Indonesia. *J. Volcanol. Geoth. Res*., 97(1-4), 55-75.

Delmelle, P., Bernard, A., Kusakabe, M., Fischer T.P., Takano B., (2000). Geochemistry of the magmatic-hydrothermal system of Kawah Ijen volcano, East Java, Indonesia. *J. Volcanol. Geoth. Res*., 97, pp. 31-53.

Giggenbach, W.F. (1980). Geothermal gas equilibria. *Geochim. Cosmochim. Ac.*, 44(12), pp. 2021-2032.

Giggenbach, W.F., Stewart, M.K., (1982). Processes Controlling the Isotopic Composition of Steam and Water Discharges from Steam Vents and Steam-Heated Pools in Geothermal Areas. *Geothermics*, 11 (2), pp. 71-80.

Glover, R.B., (1988). Boron Distribution Between Liquid and Vapour in Geothermal Fluids. *Proc. 10th New Zealand Geothermal Workshop*, New Zealand.

James, R., (1962). Steam-water critical flow through pipes. *Proc. Inst. Mech. Eng.*, 176, pp. 741-748.

Libbey, R., Murphy, J., Dermawan, F., Archady, D., Webbison, S., (2022). *Blawan-Ijen Conceptual Model ver. 2.1* [unpublished report]. Ormat Technologies, Nevada, USA.

Libbey, R., Murphy, J., Dermawan, F., Archady, D., Webbison, S., Spielman, P., Saputra, I., Husein, M., Utomo, D., Kurniawahidayati, K., Deuhart, A.T., Reynold, Z., Johnson, A., Mroczek, E., (2026) [Forthcoming]. Exploration and Conceptual Model of the Ijen Geothermal Field: Indonesia’s First Developed Blind Geothermal System. *World Geothermal Congress, Calgary, Canada.*

Lohr, A.J., De Kort, T., Van Straalen, N.M., Van Gestel, C.A.M. (2007). Unraveling the causes of the toxicity of extremely acid waters of volcanic origin. *Environ. Int.,* 33, pp. 743-749.

Marini, L., (2022). *Ijen Geochemistry result and conceptual model* [unpublished report]. STEAM srl, Pisa, Italy.

Pasqua, C., Pisani, P. (2012). *Structural Geology & Magnetotelluric/TDEM Survey of the Blawan-Ijen Geothermal Prospect* [unpublished report]. ELC-Electroconsult S.p.A., Milano, Italy.

Truesdell, A.H., Lippmann, M.J., Quijano, J.L., D’Amore, F., (1995). Chemical and Physical Indicators of Reservoir Processes in Exploited High-Temperature, Liquid-Dominated Geothermal Fields. *Proceedings of World Geothermal Congress*, Florence, Italy, 18-31 May 1995, 1933-1938.

Winick, J., Powell, T., Mroczek, E., (2011). The Natural-State Geochemistry of The Rotokawa Reservoir. New Zealand Geothermal Workshop, Auckland, New Zealand.