Study of reservoir characteristics: pH, dissolved and precipitate minerals in Atadei geothermal field, Lembata Regency, East Nusa Tenggara

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Abstract. Based on PLN reports in 2020, there are 24 surface manifestations found in the Atadei geothermal field including fumaroles/steam vents with temperatures ranging from 80°C - 98°C, hot springs with temperatures around 34 - 39.6°C, cold springs and altered rocks. Exploration wells AT-1 and AT-2 were drilled by DISDM in 2004, but no steam or water was found at depth. To determine the reservoir characteristics, geochemical modeling with PHREEQC was conducted. From the saturation index, it is known that the hot and cold springs in the study area are entirely oversaturated with silica minerals (quartz and chalcedony). This is presumably because the host rock is andesitic lava rock with a silica content of 55 - 65%. In addition, most of the springs are also oversaturated with carbonate minerals but have not yet formed deposits around the manifestations probably because the solubility of minerals in the fluid is still high (IAP < Ksp) or minerals have precipitated elsewhere. From the geochemical modeling with forward model, it is known that the reservoir characteristics in the study area in the reservoir temperature around 235°C have an acidic pH ranging from 4.6 – 4.7. This is supported by the composite log data of the AT-1 well where in the depth interval of 608 - 830.5 m, the reservoir is suspected to be a chloride sulfate type with a pH that tends to be low (acidic) characterized by the presence of acidic alteration minerals, namely pyrophyllite and dickite (Reyes, 1990).

Keywords: *Atadei geothermal field; geochemical modeling; pH; phreeqc; reservoir characteristic; saturation index.*

1 Introduction

There are at least 25 geothermal prospects along the Banda Arc spreading from Lombok to Alor with the potential to reach 700 MWe, one of which is the Atadei geothermal area. On April 28, 2017, through the Decree of the Minister of Energy and Mineral Resources Number 1894 K/30/MEM/2017, PT PLN (Persero) received an assignment to conduct geothermal exploitation in the Atadei Geothermal Working Area (WKP), Lembata Regency, East Nusa Tenggara. The area of WKP Atadei is 31,200 Ha with potential reserves of 40 MWe. Based on

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PLN report (2020), there are 24 surface manifestations found in the Atadei geothermal field, including fumaroles/steam vents/steaming ground with temperatures ranging from 80°C - 98°C, hot springs with temperatures around 34 - 39.6°C, cold springs and altered rocks.

In 2004, two exploration wells were drilled by DISDM, namely AT-1 well located inside the Watuwawer caldera - 200 meters from ATD-1 well - with a depth of 830.5 m and AT-2 well located 800 meters from ATD-1 well with a depth of 750.5 meters. As a result of drilling AT-1 well, the maximum logging temperature measured below the surface at a depth of 450 m is 145.5°C and AT-2 well is 160°C at a depth of 502m. From the drilling results of these two exploration wells, neither steam nor water was found at depth. Based on the composite log data of the exploration wells, the reservoir fluid characteristics of AT-1 well at the depth interval of 590 - 608 m show a neutral pH chloride fluid type with a temperature of around 180 - 240°C. While in the depth interval of 608 - 830.5 m, the chloride sulfate type with pH tends to be low (acidic) which is characterized by the presence of acidic alteration minerals, namely pyrophyllite and dickite.

According to PT PLN (Persero) RUPTL 2021-2030, in the year of 2026, PLN plans to develop the Atadei geothermal field with a capacity of 2 x 5 MW so that if the Atadei reservoir is acidic, it has the potential to cause problems in the future due to its corrosive nature. Mineral precipitation is closely related to temperature, permeability and reservoir fluid composition (Browne, 1978). Septianto (2016) conducted hydrogeochemical simulations to estimate the mineral composition of hydrothermal alteration and precipitates in hot springs in the North and South Bandung basins. The modeling aims to determine the minerals that may appear on the surface as precipitates or minerals in the reservoir. Therefore, to estimate the characteristics of reservoir fluids in the Atadei geothermal field, geochemical modeling is carried out through the analysis of saturation indices (dissolved and precipitated minerals) from the manifestation, estimation of reservoir pH by reacting meteoric water and host rock and comparing simulation results with exploration well drilling data.

2 Location Study

The Atadei geothermal working area (WKP) is located on Lembata Island, Lembata Regency, East Nusa Tenggara (Figure 1) with an area of 31,200 ha. Coordinately, WKP Atadei is located at 123°30'00” -125°35'00” East and 6°26'40” - 6°31'21” N-S. There are 3 (three) active volcanoes in the Atadei geothermal field, namely Ile Ape/Ile Lewotolo and Ile Werung which are on the mainland while Ile Hobal is on a small island in the Alor Strait.

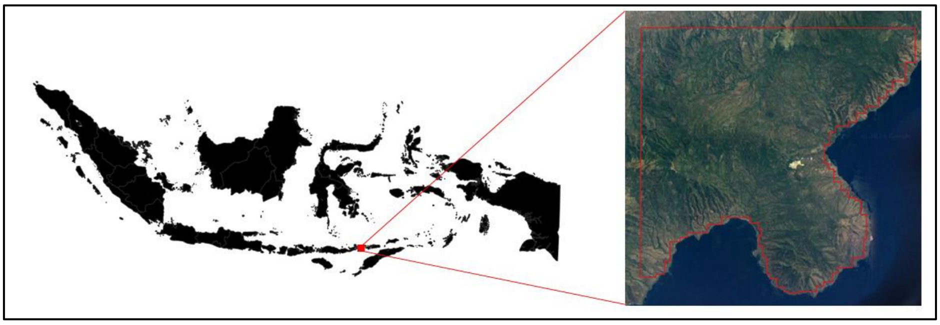

Figure 1 Atadei geothermal field location

3 Geology of study area

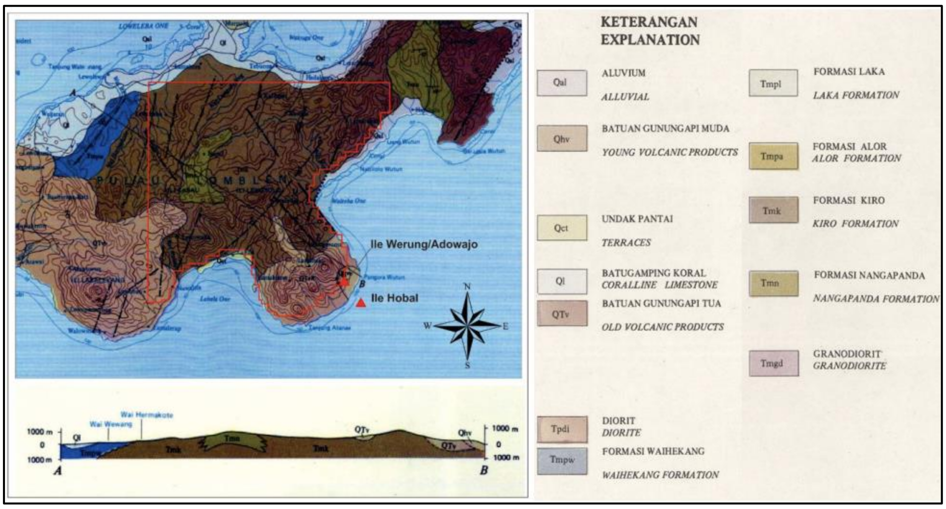

Figure 2 Geological map of Lomblen quadrangle (Koesoemadinata & Noya, 1989)

Based on the geologic map of Lomblen quadrangle, East Nusa Tenggara (Figure 2) by Koesoemadinata & Noya (1989), it is known that the Atadei geothermal working area on Lembata Island is regionally composed of (old to young order), namely:

a. Kiro Formation (Tmk) consists of lava, breccias, agglomerates, locally pumiceous tuff intercalations.
b. Nangapanda Formation (Tmn) was formed interfingering with Kiro formation that consists of sandy tuffs, tuffaceous breccia, locally sandy limestones and tuffaceous sandstone intercalations.
c. Waihekang Formation (Tmpw) consists of limestone, sandstone interbedded with tuff.

d. Old Volcano Rocks (QTv) consists of lava, breccia, agglomerate, tuff, volcano sand and pumice passive tuff.
e. Younger Volcano Rocks (Qhv) consist of lava, agglomerate, bombs, gravel, sand and volcano ash.

Based on PLN's report (2020), it is known that the rock distribution in the Atadei geothermal field is dominated by massive porphyry andesite rocks including pyroxene and plagioclase.

4 Geothermal system of study area

In Supijo's research (2018) in terms of integrated geoscience studies, mass flow modeling and heat sources, it is known that the Atadei geothermal field can be categorized as an active or recent magmatic play type with intrusive magma chamber. It is influenced by active faulting which allowing the deep rooted magmas to intrude beneath flat terrain with no volcanism. It appears part of the Watuwawer caldera. The deep leakage that hot geothermal fluid is upwelling from the deep of fracture permeability from Watuwawer Fault and Lewokebingi Fault control the flows of hot permeability-with some fluids flow laterally to the fluids-in which it ascends through the given vertical Southeast until rising to the surface through Mauraja Fault as outflow. A liquid dominated reservoir with most likely underlying thin steam caps present in three area namely Watuwawer, Lewo Kebingin and Lewo Keba is attained in the depth of -800 masl, the exception applies to the Watuwawer doming area where it reaches the depth around -700 masl.

5 Materials and method

5.1 Hydrogeochemical analysis of surface manifestation

To determine the reservoir characteristics in the Atadei geothermal field, water type analysis and fluid equilibrium of surface manifestations are carried out. The data used is primary data from PLN report (2020) where there are 24 surface manifestations found in the Atadei geothermal field including fumaroles/steam vents/steaming ground with temperatures ranging from 80°C - 98°C, hot springs with temperatures around 34 - 39.6°C, cold springs and altered rocks.

5.2 Geochemical model: SI dan forward modeling

To determine the dissolved and precipitated minerals in the spring water, saturation index modeling was conducted using PHREEQC ver. 3.7.3. PHREEQC is a computer program written in the C and C++ programming languages that is designed to perform a variety of water geochemistry calculations. PHREEQC has capabilities for (1) speciation and saturation index calculations; (2) batch-reaction and one-dimensional (1D) transport calculations with reversible and irreversible reactions; and (3) inverse modeling, which finds mineral and gas mole transfer sequences that account for compositional differences between waters within certain compositional uncertainty limits (DL Parkhurst, 2013). The database used is phreeqc.dat. Furthermore, to determine the reservoir characteristics, forward modeling was conducted (Figure 3) by reacting meteoric water and host rocks, namely andesite minerals, at several temperature variations. In this modeling, it is assumed that there is a reaction with hydrothermal gases, namely H_2S and CO_2 and presence of boiling in the reservoir.

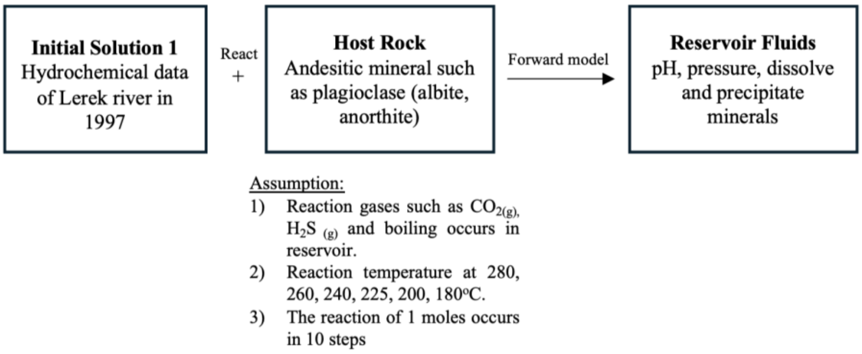

Figure 3 Reservoir characteristics prediction with forward modeling in PHREEQC software

6 Result and discussion

6.1 Hydrogeochemical analysis

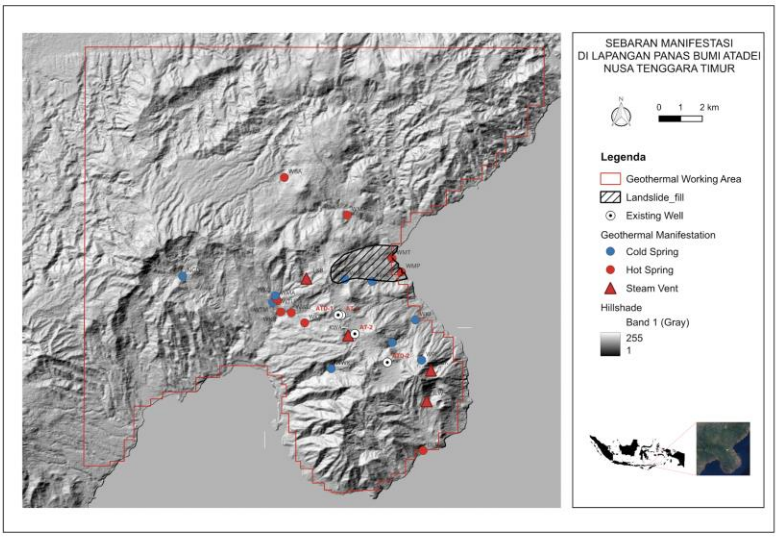

Figure 4 Map of manifestation distribution in Atadei geothermal field, East Nusa Tenggara

Based on the chemical data of the spring manifestations (Figure 4) in Attachment 1 (Table 7), it is known that the Mg concentration in the manifestations is quite high (>0.1 mg/kg) indicating that there is leaching of Mg from local rocks or mixing with meteoric water from shallow aquifers (Nicholson, 1993). Cl concentrations ranged from 2 - 35 mg/kg except at MAP WMT and MAP DLR which are located near the sea that indicate mixing with seawater due to the coastal position of both samples. The high Cl concentrations in these two hot springs do not characterize spring water from deep reservoirs because the temperatures do not reach boiling and the flow rates are < 1 L/s (Nicholson, 1993). Generally, cold springs in the study area have high SO_4 concentrations of > 1,000 mg/kg. Sulphate concentrations are usually low in fluids from deep reservoirs (<50 mg/kg), but increase as hydrogen sulphide oxidation increases. High sulphate concentrations in surface water are usually the result of vapor condensation into near-surface water (Nicholson, 1993)

To determine the type of water, plotting on the Cl – SO_4 – HCO_3 trilinear diagram is done as follows:

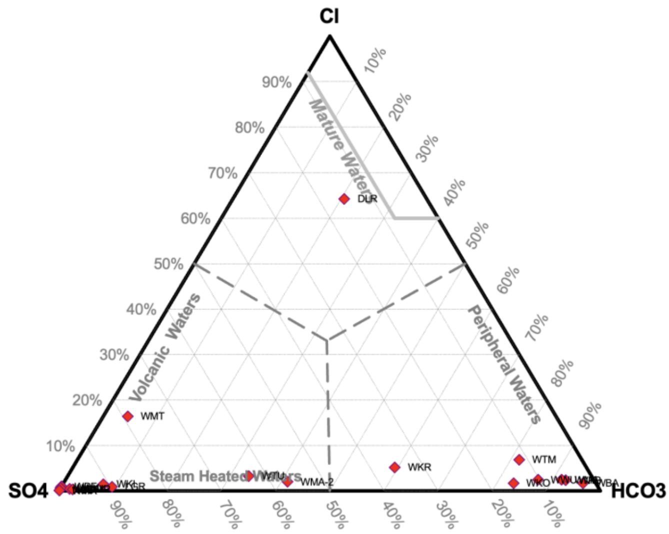

Figure 5 Cl-SO_4-HCO_3 diagram of hot and cold spring in Atadei geothermal field, East Nusa Tenggara

From Figure 5, it is known that the manifestations in the Atadei field of hot springs at the Wai Wejak location are generally of the bicarbonate type. In Jasim et al (2018), the provisional interpretation of water with the dominant anion HCO_3 usually indicates the thermodynamic equilibrium of the reservoir rock at the boundary of the magmatic-hydrothermal system or (already towards the surface) (Nicholson, 1993). In the Wai Teba area, springs are generally sulphate-type because they have a high SO_4^{2-} content. The cold springs scattered in Atadei are generally of low pH and sulphate type. The sulphate-type are thought to be the result of condensation of hydrothermal gases into shallow groundwater and contain low Cl anions (Jasim et al, 2018).

Fluid equilibrium can be analysed using the Na-K-Mg diagram so that it can be known whether the manifestation is included in immature water, partial equilibrium and full equilibrium which is useful for estimating reservoir temperature.

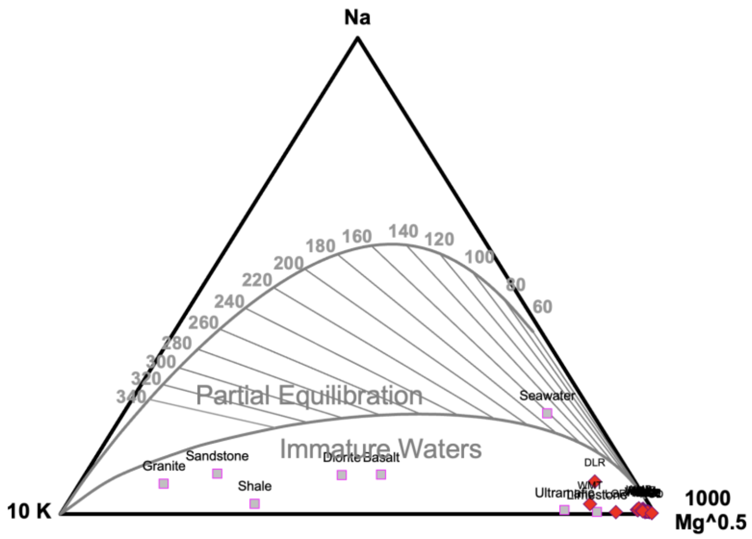

Figure 6 Na-K-Mg diagram of hot and cold spring in Atadei geothermal field, East Nusa Tenggara

Based on the Na - K - Mg diagram (Figure 6), it is known that all manifestations in the Atadei geothermal field are included in immature water, which means that they have experienced mixing with meteoric water so that the no manifestation that represents deep reservoir fluid.

6.2 Geochemical modeling

6.2.1 Saturation index (SI)

Mineral saturation calculations using the saturation index (SI) can assist in predicting the existence of reactive minerals. When SI=0, the balance between dissolved ions and a solid mineral has been reached, that is, saturation has been reached. On the other hand, SI>0 indicates oversaturation, so the mineral will tend to precipitate to achieve balance. When SI<0, water is undersaturated with respect to the mineral phase, so it will tend to dissolve until the balance is reached (Appelo & Postma, 2005 at J.R.Reyes-Santiago et al., 2021). To determine the dominant minerals in the spring water in the study area, saturation index modeling was carried out with PHREEQC software and the following results were obtained:

Table 1 Analysis of dissolved and precipitated minerals in hot and cold spring with PHREEQC in Atadei geothermal field, East Nusa Tenggara

No.	Sample code	Temp. (ºC)	pH	Saturation Index (PHREEQC)						
				Carbonate			Sulphate		Silica	
				Aragonite	Calcite	Dolomite	Anhydrite	Gypsum	Quartz	Chalcedony
1	WMR	30,1	2,5	Not identified			-0,09	0,15	1,24	0,82
2	WPE	26,7	3,2	Not identified			-0,77	-0,49	0,90	0,48
3	WTM	27,2	7,6	-0,26	-0,11	-0,25	-2,78	-2,50	0,75	0,33
4	WKO	25,1	7,2	-0,77	-0,63	-1,36	-2,77	-2,46	0,71	0,28
5	WKB	38,3	8,4	0,81	0,98	1,90	-2,92	-2,75	0,91	0,52
6	WMA	33,4	8,1	0,21	0,36	0,64	-3,14	-2,93	0,96	0,56
7	WWU	38,2	8,7	0,16	0,32	0,72	-2,93	-2,76	0,79	0,40
8	WTU	39,6	8,1	0,59	0,76	1,68	-1,41	-1,26	1,18	0,79
9	WHK	30,8	5,9	-1,74	-1,59	-3,42	-0,27	-0,03	0,97	0,56
10	WMP	35,5	7,3	-0,03	0,13	0,25	-0,15	0,04	0,47	0,08
11	WMT	34	8,7	1,18	1,34	3,08	-0,53	-0,32	0,58	0,18
12	WBA	36,7	7,67	0,17	0,33	0,51	-3,22	-3,04	0,92	0,53
13	WMA-2	34,5	6,89	-0,99	-0,83	-1,95	-1,85	-1,65	0,56	0,16
14	WWK	29,9	3,3	Not identified			-0,75	-0,50	1,24	0,83
15	WKR	37,7	8,35	0,65	0,81	1,56	-2,02	-1,85	0,92	0,53
16	WKI	28,1	8,52	1,42	1,56	2,83	-0,33	-0,06	1,02	0,60
17	LGR	27,7	8,1	0,80	0,95	1,57	-0,57	-0,30	0,89	0,46
18	NGD	25,8	2,9	Not identified			-0,52	-0,22	1,45	1,03
19	DLR	37,8	8,01	0,85	1,02	2,35	-1,60	-1,43	1,09	0,70

Based on Table 4, it is known that the distribution of hot and cold springs in the study area is entirely oversaturated with silica minerals. This is thought to be because the host rock in the study area is andesite lava rock with a silica content of 55-65%. The condition of sulphate minerals is undersaturated in all springs except in WMP hot spring which is equilibrated with gypsum minerals (SI = 0.04). Most of the springs in the study area also oversaturated with carbonate minerals but have not formed travertine deposits around the manifestations probably because the solubility of minerals in the fluid is still high (IAP < Ksp) or not saturated so there's no mineral deposits occur or minerals have precipitated elsewhere.

6.2.2 Reservoir Characteristics (pH, dissolve and precipitate minerals)

The research focus for reservoir characteristics estimation is on the Watuwawer geothermal system where there are AT-1 and AT-2 wells. The estimation of subsurface temperature used as a reservoir modeling parameter of the research area is based on CO_2/H_2 and H_2S/H_2 geothermometer of the KWA steam vents, it is estimated that the reservoir temperature in the system is around 235°C (PLN, 2020). From the composite log of the AT-1 well found a high temperature alteration mineral, epidote, so it is suspected that the reservoir temperature ranges between 180 - 240°C. In addition, pyrophyllite minerals were also found which are thought to form in the temperature range of 200 - 280°C (Reyes, 1990).

Forward modeling in PHREEQC is carried out by reacting meteoric water (Table 5) from the recharge zone with host rocks under certain temperature conditions. In addition, conditions that may occur in the reservoir are added including hydrothermal gases (CO_2, H_2S), boiling and ion exchange so that the following results are obtained:

Table 2 Chemical composition of meteoric water from Lerek river in 1997

Temperature	25	°C	**SiO_2**	82,26	mg/L
pH	8,40		**Cl**	4,67	mg/L
Li	0,05	mg/L	**SO_4**	0	mg/L
Na	7,81	mg/L	**HCO_3**	111,58	mg/L
K	0,43	mg/L	**F**	0	mg/L
Ca	26,02	mg/L	**^{18}O**	-6	‰
Mg	3,90	mg/L	**^{2}H**	-38	‰
B	0	mg/L			

Table 3 Forward modeling of geothermal reservoir characteristics in Atadei, East Nusa Tenggara

No	**Temp.**	**Amount added to the reaction**	**Pressure**	**pH**	**Minerals (SI)**	
	°C	mol	atm		Dissolve	Precipitate
1	280	0,1	61,88	4,29	Anhyhidrite (-2.5) Gypsum (-4.19) Calcite (-0.95) Dolomite (-2.63) Aragonite (-2.39)	Illite (9.71) Kaolinite (12.43) Pyrite (0.23) Quartz (1.71) Chalcedony (1.71)
2	260	0,2	44,56	4,46	Anhyhidrite (-2.31) Gypsum (-3.19) Calcite (-0.07) Dolomite (-1.11) Aragonite (-1.42)	Illite (12.39) Kaolinite (13.99) Pyrite (1.92) Quartz (2.18) Chalcedony (2.16)
3	240	0,3	31,20	4,64	Anhyhidrite (-2.07) Gypsum (-3.55) Dolomite (-1.11) Aragonite (-0.62)	Hematite (7.56) Geothite (2.47) Illite (14.48) Kaolinite (15.12) Pyrite (3.51) Quartz (2.53) Chalcedony (2.49) Calcite (0.65)

No	Temp.	Amount added to the reaction	Pressure	pH	Minerals (SI)	
	°C	mol	atm		Dissolve	Precipitate
4	225	0,4	23,26	4,77	Anhyhidrite (-1.66) Gypsum (-3.07) Aragonite (-0.05)	Illite (16.17) Kaolinite (16.07) Pyrite (4.73) Calcite (1.14) Dolomite (1.08) Quartz (2.81) Chalcedony (2.76)
5	200	0,5	13,64	5,00	Anhyhidrite (-1.17) Gypsum (-3.07)	Illite (18.23) Kaolinite (17.17) Pyrite (6.26) Calcite (1.73) Dolomite (2.2) Quartz (3.14) Chalcedony (3.05) Aragonite (0.67)
6	180	0,6	8,68	5,18	Anhyhidrite (-0.89) Gypsum (-2.04)	Illite (20.09) Kaolinite (18.22) Pyrite (7.19) Calcite (2.14) Dolomite (2.96) Quartz (3.44) Chalcedony (3.32) Aragonite (1.2)

According to Nicholson (1993), in high temperature reservoirs, the neutral pH is around 5.5. Based on Table 6, it is known that the reservoir characteristics by reacting meteoric water and host rock reaction with hydrothermal gases (CO_2 and H_2S), the presence of boiling, at reservoir temperature around 235°C have an acidic pH ranging from 4.6 – 4.7. This is supported by the composite log data of AT-1 well where in the depth interval of 608 - 830.5 m, the reservoir is suspected to be a chloride sulphate type with a pH that tends to be low (acidic) characterized by the presence of acidic alteration minerals, namely pyrophyllite and dickite (Reyes, 1990).

7 Conclusions

The conclusions of the study are as follows:

1. In the distribution of hot and cold springs in the study area, all springs are oversaturated with silica minerals (quartz and chalcedony). This is presumably because the host rock in the study area is andesite lava rock with a silica content of 55 - 65%. Most of the springs in the study area are oversaturated with carbonate minerals but have not yet formed deposits around the manifestations probably because the solubility of minerals in the fluid is still high (IAP < Ksp) or minerals have precipitated elsewhere.

2. From the results of geochemical modeling with forward modeling in PHREEQC, namely by reacting meteoric water originating from the recharge zone with host rock, considering the presence of CO_2(g), H_2S(g) and boiling effects, it is known that the reservoir characteristics in the study area at reservoir temperature around 235°C have an acidic pH ranging from 4.6 – 4.7. This is supported by the composite log data of AT-1 well where in the depth interval of 608 - 830.5 m, the reservoir is suspected to be a chloride-sulphate type with a pH that tends to be low (acidic) characterized by the presence of acidic alteration minerals namely pyrophyllite and dickite (Reyes, 1990).

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Attachment 1.

Table 4 Physical & Chemical composition of spring manifestation in Atadei geothermal field, Lembata Regency, East Nusa Tenggara (PLN, 2020)

No	Sampling code	Location	Manifestation type	Temp. ºC	pH	Li	Na	K	Ca	Mg	B mg/kg	SiO_2	Cl	SO_4	HCO_3	F
1	WMR	Atalojo	Cold spring	30,1	2,5	0,17	185,85	28,46	429,53	310,64	16,52	122,98	10,46	14.065,65	-	5,44
2	WPE	Lerek	Cold spring	26,7	3,2	0,03	14,08	2,99	118,25	12,26	75,40	111,87	35,31	3.615,54	-	2,92
3	WTM	Wai Wejak	Cold spring	27,2	7,6	-	16,64	3,39	28,14	11,91	0,41	82,19	14,33	24,18	170,62	0,48
4	WKO	Wai Wejak	Cold spring	25,1	7,2	0,03	15,68	2,90	27,95	10,00	0,15	32,27	2,84	25,31	138,01	0,20
5	WKB	Wai Wejak	Hot spring	38,3	8,4	0,01	17,76	4,78	39,13	14,15	0,29	84,77	4,67	10,84	189,84	0,22
6	WMA	Wai Wejak	Hot spring	33,4	8,1	0,01	12,05	4,61	24,18	8,45	0,13	78,09	3,96	9,78	149,48	0,36
7	WWU	Wai Wejak	Hot spring	38,2	8,7	0,03	33,04	5,45	19,95	9,95	0,19	62,13	4,24	18,25	153,89	0,33
8	WTU	Wai Wejak	Hot spring	39,6	8,1	0,03	57,31	18,09	63,98	42,88	4,49	85,31	18,50	353,62	186,78	1,29
9	WHE	Wai Teba	Cold spring	30,8	5,9	0,02	100,12	32,06	509,40	145,44	0,04	70,78	8,13	2.123,56	39,56	0,86
10	WMP	Wai Teba	Hot spring	35,5	7,3	0,07	212,65	37,52	590,02	289,68	0,17	26,06	9,74	2.856,28	71,06	0,24
11	WMT	Wai Teba	Hot spring	34	8,7	0,04	432,38	208,73	272,00	342,88	0,10	35,51	538,21	2.598,52	148,44	0,95
12	WBA	Ilekimok	Hot spring	36,7	7,67	0,09	14,13	4,28	38,11	10,97	0,24	78,57	3,82	5,39	218,23	0,23
13	WMA-2	Ilekimok	Hot spring	34,5	6,89	0,01	16,42	5,17	36,26	8,61	1,08	31,47	5,48	158,91	115,37	0,23
14	WWK	Lusilame	Cold spring	29,9	3,3	0,01	39,58	8,37	137,92	20,69	11,97	127,73	12,26	1.972,20	-	0,89
15	WKR	Lusilame	Hot spring	37,7	8,35	-	17,80	4,38	42,73	15,64	0,10	83,92	12,77	86,37	145,25	0,94

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16	WKI	Lewogroma	Cold spring	28,1	8,52	0,01	65,84	21,51	516,81	127,74	0,09	77,14	28,54	1.797,19	149,09	1,57
17	LGR	Lewogroma	Cold spring			0,02	31,76	62,48	352,10	81,26	0,18	53,74	11,84	1.128,80	117,42	0,65
18	NGD	Nogodoni	Cold spring			-	15,22	3,86	230,77	57,48	96,50	182,11	5,43	3.344,16	-	1,29
19	DLR	Dulir	Hot spring			0,28	710,06	69,93	91,37	80,57	4,38	120,36	1.301,17	305,83	416,97	1,28