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GEOTHERMAL REGIME AND GEOCHEMISTRY OF HOT SPRINGS IN MOUNT SABALAN (NORTHWEST OF IRAN)

The district of the Mount Sabalan is regarded as the best place to investigate geothermal activity within the northwest Iran. Since the last episode of volcanic activity in the Plio-Quaternary time, hot springs and surficial steam as a conspicuous manifestation of geothermal activity around slopes of the Mount Sabalan. Hot fluids circulating in this geothermal field contain anions chiefly of HCO_3^- and Cl^-; however, SO_4^{2-} content in some water samples is relatively high, imparting sulfate characteristics to such fluids. Geothermometric studies provided compelling evidence for estimation of the reservoir temperature (~150 °C) in the study areas. In this respect, the geothermal systems in the eastern slope of the Mount Sabalan were categorized as high-temperature ones. Hot springs within the Sarein area contain the highest Na^+ content. The highest Ca^{2+} content belongs to hot springs in the Sardabeh and Yeddiboloug areas. The maximum concentration values for K and Mg are 40 and 20 mg/dm^3, respectively. The information on the dissolved silica concentration in a water solution could be used as a geothermometer. The fracturing provided a suitable secondary permeability and facilitated the upward migration of high-temperature geothermal fluids.

Keywords: Geothermal conditions, geochemistry, temperature, geothermometers, dissolved silica, Iran, Sabalan

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ГЕОТЕРМИЧЕСКИЕ УСЛОВИЯ И ГЕОХИМИЯ ГОРЯЧИХ ИСТОЧНИКОВ ГОРЫ САБАЛАН (СЕВЕРО-ЗАПАДНЫЙ ИРАН)

Район горы Сабалан выбран в качестве лучшего объекта для изучения геотермальной активности в северо-западном Иране. Начиная с последнего эпизода вулканической деятельности в плио-четвертичное время, горячие источники и проявления пара на поверхности являются свидетельством геотермальной активности вдоль склонов горы Сабалан. Горячие флюиды, циркулирующие в этом геотермальном поле, содержат в основном анионы HCO_3^- и Cl^-; однако содержание SO_4^{2-} в отдельных пробах воды сравнительно высокое, свидетельствующее о сульфатных свойствах этих флюидов. Исследования с использованием геотермометров показывают, что пластовая температура оценивается в (~150 °C) на изучаемой площади. В этой связи геотермальная система восточной части горы была охарактеризована как высокотермальная. Горячие источники на площади Сарейн (Sarein) имеют максимальное содержание Na^+. Наибольшее содержание Ca^{2+} связано с горячими источниками площадей Сардабех (Sardabeh) и Еддиболуг (Yeddiboloug). Максимальное содержание для K и Mg – 40 и 20 мг/дм^3 соответственно. Информация по концентрации кремнезема в пробах воды может быть использована в качестве геотермометра. Трещиноватость создает вторичную проницаемость и способствует выходу высокотемпературных геотермальных флюидов.

Ключевые слова: геотермические условия, геохимия, температура, геотермометры, растворенный кремнезем, Иран, Сабалан

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ГЕАТЭРМІЧНЫЯ ЎМОВЫ І ГЕАХІМІЯ ГАРАЧЫХ КРЫНІЦ ГАРЫ САБАЛАН (ПАЎНОЧНА-ЗАХОДНІ ІРАН)

Мясцовасць гары Сабалан выбрана ў якасці найлепшага аб’екту для вывучэння геатэрмальнай актыўнасці ў паўночна-заходнім Іране. Пачынаючы з апошняга эпізоду вулканічнай дзейнасці ў пліа-чацвярцічны час, праявы гарачых крыніц вады і пару на зямной паверхні сведчаць аб геатэрмальнай актыўнасці ўздоўж схілаў гары Сабалан.

Гарачыя флюіды, якія цыркуліруюць у гэтым геатэрмальным полі, утрымліваюць галоўным чынам аніёны HCO_3^- і Cl^-; аднак ўтрыманне SO_4^{2-} у асобных пробах вады параўнальна высокае, што сведчыць аб сульфатных якасцях гэтых флюідаў. Даследаванні з выкарстаннем геатэрмометраў адзначаюць, што тэмпература ў калектары ацэньваецца прыкладна ў 150 °C на вывучаемай плошчы. Ў гэтай сувязі геатэрмальная сістэма ўсходняй часткі гары была вызначана як высокатэрмальная. Гарачыя крыніцы на плошчы Сарэйн (Sarein) утрымліваюць максімальную колькасць Na^+. Найвялікшае ўтрыманне Ca^{2+} адзначана на плошчах Сардабех (Sardabeh) і Еддзіболуг (Yeddiboloug). Максімальнае ўтрыманне для K і Mg – 40 і 20 мг/дм^3 адпаведна. Дадзеныя па канцэнтрацыі крэмнязёму ў водным растворы могуць быць выкарыстаны ў якасці геатэрмометра. Трэшчынаватасць ставарае другасную прапушчальнасць і садзейнічае выхаду высокатэмпературных геатэрмальных флюідаў.

Ключавыя словы: геатэрмічныя ўмовы, геахімія, тэмпература, геатэрмометры, растворы крэмнязём, Іран, Сабалан

1. Introduction. Geothermal research is used to identify the origin of geothermal fluids and to quantify the processes that govern their composition and the associated chemical and mineralogical transformations of rocks interacting with fluids. A variation in the chemistry of geothermal fluids provides the information regarding their origin, mixing, and flow regimes of the systems [1]. Their subject has a strong applied component. The chemistry constitutes an important tool for an exploration of geothermal resources and in assessing the production characteristics of drilled geothermal reservoirs and their response to production. Geothermal fluids are also of interest as analogues to ore-forming fluids. Thermodynamic and kinetic experiments and numerical modeling of fluid flow [2] have advanced understanding of chemical processes within active geothermal systems.

The Mount Sabalan in the northwest of Iran is a part of the Azerbaijan crustal block. The map of geologic structure of Mount Sabalan and the Moeil Valley is shown in (fig. 1).

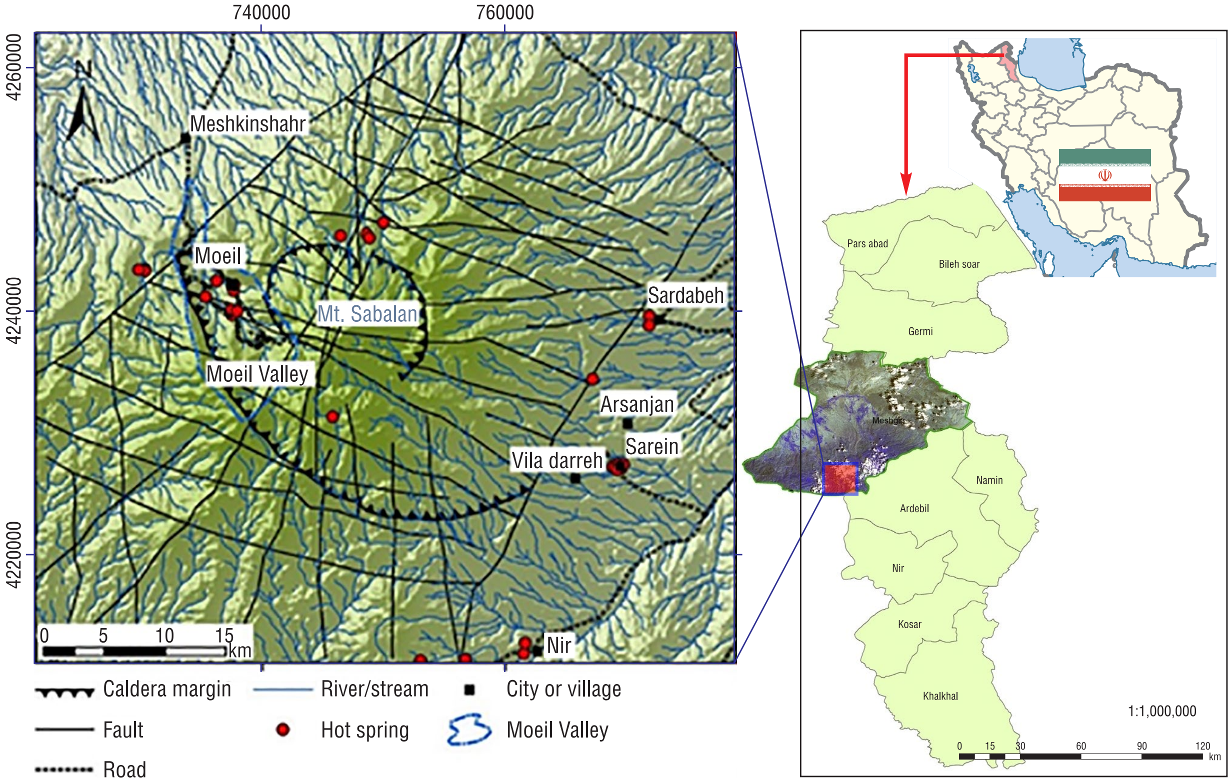

Fig. 1. Mount Sabalan area, northwestern Iran and positions of known hot springs [3]

From the geotectonic point of view, this block is situated in between the Arabian and Eurasian plates [4, 5]. In fact, the Sabalan volcano is a part of a volcanic belt stretching from the Caspian Sea in the east to the Black Sea in the west [6]. A volcanic activity along this belt is observed in various parts of Armenia, Anatolia, and western Alborz within Iran. The geothermal gradient in young volcanic regions is normally higher with a number of geothermal anomalies. It was reported by various researchers in the early twentieth of the last century in many countries, having such anomalously high geothermal gradients in potential areas, to do attempts to harness this endless geothermal energy accumulated beneath the ground surface.

The area around the Mount Sabalan within the northwest Iran was geothermally active during the Plio-Quaternary time [7]. Also higher surficial geothermal anomalies were distinguished within other parts of the country [8]. Thus, these areas were recognized to be very important, and hence, were regarded as the first priority ones for exploration and exploiting the geothermal resources. The primary outline of geothermal systems including hot springs and surficial steams in many areas around the Mount Sabalan is indicative of a widespread young subsurface magmatic activity in this region.

In general numerous hot springs and hot areas, based on available manifestations of the volcanic rocks (according to the Geological Survey of Iran) are spread all over the whole territory of Iran.

2. Geology, tectonics and hydrology of the Sabalan area. *2.1. Geology.* The Mt. Sabalan region lies on the South Caspian Plate, which underthrusts the Eurasian Plate to the north. It is in turn underthrust by the Iranian Plate, which produces compression in a northwestern direction. Geological structures in this area are complicated further by a dextral rotational movement caused by the northward underthrusting of the nearby Arabian Plate beneath the Iranian Plate. There is no Benioff-Wadati zone to indicate any present-day subduction. Due to this tectonic framework, the Cenozoic geologic history and stratigraphy of the region are complex, with units of different structural characteristics [3, 9 – 13]. The geologic structure map of the eastern slope of Sabalan is shown in fig. 2.

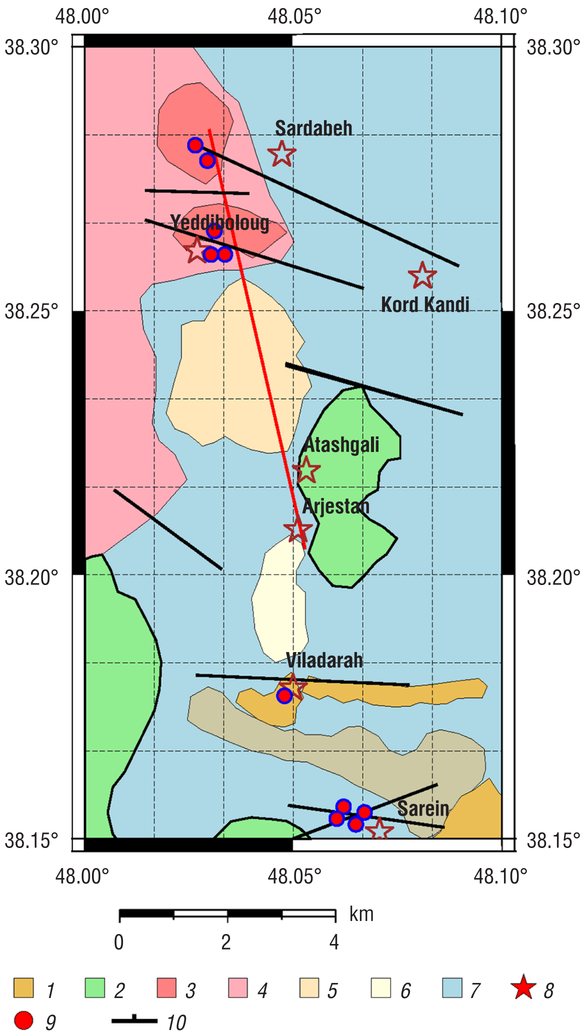

Fig. 2. Hot springs of the eastern slope of the Mount Sabalan: *1* – alternation of tuff and lahar (Quaternary); *2* – alluvial terraces (Quaternary); *3* – amorphous silica deposit (Quaternary); *4* – porphyritic basalt and andesite (Quaternary); *5* – Fe and Mn mineralization (Quaternary); *6* – andesite and trachyte (Pliocene); *7* – condlomerate with volcanic ash (Quaternary); *8* – residential area; *9* – hot springs; *10* – faults

Igneous activity began in the Eocene with an accumulation of potassic alkalic volcanics over a sequence of Mesozoic and Paleozoic sediments. These rocks were intruded and thermally metamorphosed by an Early Miocene monzonitic batholith, which is elongated in a NW–SE direction and is exposed on the western ridge of the Mount Sabalan. Significant uplift and erosion of the batholith followed, and a sequence of Late Miocene sediments were deposited to the southwest and southeast of the batholith [14].

2.2. Tectonics. The volcanic axis of the Sabalan area is completely covered by sediments. Thus, its structure cannot be identified. Analysis of aerial photos has pointed out two main fracture systems, one trending approximately NE–SW, prevailing over almost the whole area and integrated with a second, trending NW–SE, prevailing in the southeast sector. Minor fractures trending N–S and E–W also present. The density of the total fracture field has its maximum in correspondence with the summit of the Sabalan Massif. The gravimetric highs defined in the residual gravity map are in the northeast, west and south of the Sabalan massif and bear out the hypothesis of a structural high centered on the volcanic massif itself, which can be correlated with intrusive magmatic stocks. Local negative gravimetric minima are in Ahar–Meshkin Shahr–Lahrood, those of Nir–Ardebil and at the basin of Sarab. The anomalies are bounded by gravimetric faults that probably indicate their tectonic origin. The Meshkin Shahr area (outside the map frame) corresponds to the northern edge of the two gravimetric structural highs, one trending E–W (Sabalan west), the other NE–SW (Sabalan NE) which converge towards the area of the Sabalan massif. Geothermal springs are at the boundary of these structural highs and the Ahar–Meshkin Shahr–Lahrood Depression. The connection between the thermal springs and the fracture, bordering the structural high, seems evident for this area. In the Sarein area, west of Ardabil, thermal springs are located inside the Nir–Ardebil Depression.

2.3. Hydrology. The geothermally interesting hydrological characteristics of the sedimentary substratum can be summarized as follows: a) precambrian rocks are mainly composed of limestone, dolomite and sandstone and have a good permeability. Permo-Triassic succession, made of quartzites alternating with limestone and dolomites, has good permeability; b) the Shemshak formation, composed of shales, siltstones and sandstones has a very low permeability and can act as a good caprock; c) magmatic intrusions are permeable because of fracturing, mostly in their upper part; d) volcanites of the Oligo-Quaternary succession, made up mainly of lava, are permeable because of fractures; e) pyrociastic deposits and altered zones have medium to low permeability. In the north of the district, the dominant lithological units are trachyandesitic, dacitic, and basaltic lavas with porphyry texture manifested by plagioclase and occasionally pyroxene and amphibole phenocrysts [15].

3. Hydrogeochemistry. Hydrogeochemistry is an indispensable unit of hydrogeological studies. It aids in the determination of chemical properties and the overall qualities of groundwater, including their genesis and relationship with surface and rain waters. So far, little work on geothermal fluids has been carried out to the east of Mount Sabalan, and most of the previous studies were done on geothermal activities in other areas around the Mount Sabalan [16–19].

Despite the lack of deep drilling data, the important subjects such as hydrogeochemical characteristics of the fluids, isotopic issues, geologic conditions governing the geothermal reservoirs, lithological compositions, and fluid-feeding localities in the study area, all they merit more detailed investigations. Hydrogeochemical studies were used as the most suitable method to consider the potential geothermal characteristics of the district with the aim of approaching to applicable estimates of the geothermal energy potential.

Some of geochemical parameters, which could be applicable to get the geothermal information for the considered area, are shown in the Table 1 [6] . It was reworked and simplified and only parameters useful for estimation of temperature by geothermometric method were kept there. The data obtained from chemical analysis (major cations and anions, surface temperature hot water and hot springs flow rate) are listed there. From the physico-chemical point of view, the hot springs in the Sabalan region demonstrate characteristics of surficial geothermal fluids (acid-sulfate waters), and the physico-chemical parameters of these hot waters vary in a wide range. The maximum temperatures at the point of discharge belong to hot springs in the Sarein area (~53 °C) and the minimum ones are related to those in the Villadara area (~20 °C). The measured total dissolved solutes (TDS) in geothermal waters in this region exhibit a direct relationship with the temperature of hot springs, so that the maximum measured TDS belongs to samples from the Sarein area (TDS = 1016 mg/dm^3) and the minimum to ones from the Viladara area (TDS = 275 mg/ dm^3).

The concentration of cations and anions in the hot springs, fig. 3, representing the above-mentioned areas are not similar and show different distribution patterns. However, an overall trend for cations like $Ca^{2+} > Na^+ > K^+ > Mg^{2+}$ and for anions like $SO_4^{2-} > HCO_3^- > Cl^-$ can be observed (fig. 4). Among other cations, the highest concentration values have Na^+ (240 mg/dm^3) and Ca^{2+} (198 mg/dm^3). Hot springs in the Sarein area contain the highest Na^+ content. The highest Ca^{2+} content belongs to the hot springs in the Sardabeh and Yeddiboloug areas.

Among the major anions, the maximum concentration values of the sulfate (SO_4^{2-} = 528 mg/dm^3) and bicarbonate (HCO_3^- = 439 mg/ dm^3) belong to samples from the Sardabeh and Sarein areas, respectively. Chloride ion (Cl^-), relative to the other two, has a lower concentration, with a maximum value of 214 mg/dm^3 in the Sarein area. The silica content of the geothermal fluids to the east of Mount Sabalan

Table 1. **Physico-chemical parameters, chemical analyses, and isotopic composition data for the selected hot spring water samples from geothermal field to the east of Mount Sabalan. The sign (–) stands for a lack of analytical data [6, modified]**

Sample ID	Sampling station	TDS, mg/dm^3	Elev., m	Flow rate, dm^3/min	*T*, °C	Na, mg/dm^3	K, mg/dm^3	Na/K ratio	T_{NaK}, °C	Cl^-, mg/dm^3	SO_4^{2-}, mg/dm^3	SiO_2, mg/dm^3	T_{SiO_2}, °C
ES1	Sarein	1016	1670	600	50	179	39.1	4,58	290.9	199	96.0	98.0	132.8
ES2	Sarein	936	1670	80	53	191	36.0	5,31	268.0	209.0	96.0	105.0	136.1
ES3	Sarein	396	1620	30	25	19	3.8	5.00	277.0	11.0	58.0	73.0	119.6
ES4	Sarein	277	1620	4	26	13	2.5	5.20	271.0	5.0	48.0	78.0	122.5
ES5	Sarein	910	1620	50	52	172	34.8	4,94	278.8	209.0	96.0	103.0	135.2
ES6	Sarein	910	1650	45	52	240	40.0	6.00	250.3	194.0	170.0	60.0	111.2
ES7	Sarein	–	1676	60	53	202	36.7	5.50	262.6	214.0	–	44.9	99.4
ES8	Sarein	–	1685	25	44	202	34.6	5.84	254.2	3.0	3.4	46.7	101.0
ES9	Sarein	–	1685	30	45	198	34.6	5.72	257.0	–	–	46.6	100.9
ES10	Sarein	–	1690	45	45	200	34.9	5.73	256.8	–	–	47.5	101.7
ES11	Sarein		1670	60	46	200	35.0	5.71	257.2			47.9	102.0
ES12	Sardabeh	830	1900	–	36	21	6.6	3.18	356.4	6.0	480.0	85.0	126.3
ES13	Sardabeh	876	1910	60	36	23	6.3	3.65	329.9	2.0	480.0	84.0	125.8
ES14	Sardabeh	891	1930	150	37	22	7.0	3.14	358.9	2.0	528.0	81.0	124.2
ES15	Sardabeh	510	1945	3	22	15	2.5	6.0	250.3	–	231.0	56.0	108.3
ES16	Sardabeh	777	1900	3	22	20	6.3	3.17	356.9	4.0	442.0	68.0	116.5
ES17	Sardabeh	–	1890	10	34	23	6.8	3.38	344.4	–	–	37.7	92.7
ES18	Sardabeh	–	1907	20	33	24	7.0	3.43	341.7	–	–	38.3	93.3
ES19	Sardabeh	–	1966	25	27	0.03	0.0	N/A	N/A	0.0	–	27.7	81.4
ES20	Sardabeh	–	1934	60	35	25	6.8	3.68	328.6	6.0	–	36.0	91.0
ES2l	Sardabeh	–	1915	15	28	22	6.7	3.28	350.1	–	–	38.4	93.4
ES22	Yeddiboloug	–	1970	60	35	26	6.6	3.94	316.2	–	6.5	35.8	90.7
ES23	Yeddiboloug	–	1930	45	34	23	7.0	3.29	350.0	–	–	36.5	91.5
ES24	Yeddiboloug	–	1950	30	36	23	6.8	3.38	344.4	–	6.5	38.1	93.1
ES25	Yeddiboloug	–	1940	25	32	23	6.8	3.38	344.4	–	–	37.5	92.5
ES26	Viladara	275	1850	400	21	14	3.1	4.52	293.1	3.0	37.0	79.0	123.1
ES27	Viladara	369	1840	600	22	23	7.0	3.29	350.0	5.0	44.0	98.0	132.9
ES28	Viladara	288	1830	15	22	12	2.0	6.00	250.3	4.0	12.0	84.0	125.8
ES29	Viladara	390	1850	6	20	25	6.6	3.79	323.2	4.0	35.0	106.0	136.6
ES30	Viladara	430	1793	30	23	32	8.6	3.72	326.4	6.0	37.0	118.0	141.7

displays a wide range (27–118 mg/ dm^3) and the maximum values belong to the springs in the Viladara (118 mg/ dm^3) and Sarein (105 mg/ dm^3) areas.

4. Subsurface temperatures. Our estimates of temperatures were fulfilled using two kinds of geothermometers, namely silica content and the Na/K ration as more frequently used [21]. Besides them there are known geothermometers based on ion exchange reactions that have temperature-dependent equilibrium constants. The respective columns Na/K ratio, $T_{Na/K}$ (°C) and T_{SiO_2} (°C) with results of our calculations were inserted into the table 1. For the Na-K geothermometers there were proposed three different formulas [22].

We used the Na–K geothermometers (100–275 °C) for hot springs of the eastern slope of the Mount Sabalan based on the following relationship:

$$t,\,°\mathrm{C} = \frac{856}{\log\left(\frac{\mathrm{Na}}{\mathrm{K}}\right) + 0.857} - 273.15,$$

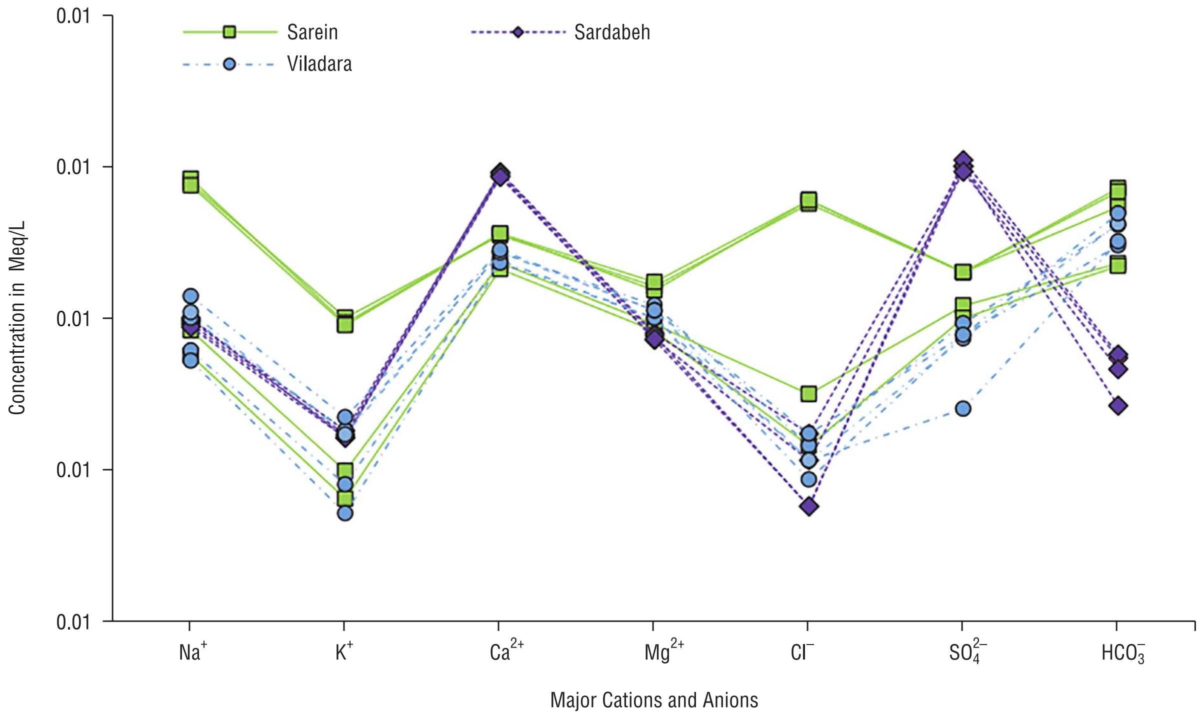

Fig. 3. Concentration variations of major cations and anions for the geothermal water samples to the east of the Mount Sabalan [20]

Na–K geothermometers [23–28] are based on ion exchange between albite-microcline, albite adularia or Na–K montmorillonite and water. The reactions on which this geothermometer is based take longer to reach equilibrium at a given temperature than those on which other common geothermometers are based and estimates, therefore, often give relatively high temperatures originating in the deeper part of a system where waters reside for relatively long periods.

Temperature estimates could be obtained using the wide spread silica thermometer. The solubility of most common silica minerals have been determined experimentally as functions of temperature at the vapor pressure of the solution. Pressure and added salts have little effect on the solubility of quartz and amorphous silica below 300 °C. Assumptions for the use of silica geothermometers are: 1) a particular silica mineral controls a dissolved silica concentration; 2) no silica precipitation occurs during ascent of a geothermal fluid from the reservoir to the surface because of conductive or adiabatic cooling; 3) silica geothermometry applied to warm spring waters is not likely to give higher temperatures than 230–250 °C because quartz dissolves and precipitates very quickly in response to changing temperature at ~ 230 °C [29, 30].

$$T = 1533.5/(5.768 - \log SiO_2) - 273.15$$
$$(\pm 2\ °C \text{ in the range } +125 \ldots +275\ °C)$$

In general the mixing process of deep and surface waters in springs affect the results of all geothermometers. As it was mentioned the silica thermometer is widely used. Due to the good correlation between Na and K in chloride-bicarbonate and chloride-sulfate waters, which means that the Na and K ratios are less affected by mixing (for these two water types), the Na-K geothermometer probably yields the most reliable temperature.

5. Discussion. The prediction of subsurface temperature in geothennal fields is one of the most important aims of geothermal investigation. Chemical (also isotopic) geothermometers are widely used to estimate reservoir temperature. Chemical geothermometers are based on the assumption that temperature dependent mineral solute equilibria are attained in the geothermal reservoir.

The solubility of most common silica minerals have been determined experimentally as functions of temperature at the vapor pressure of the solution. Pressure and added salts have little effect on the solubility of quartz and amorphous silica below 300 °C. This information allows the dissolved silica concentration in a hydrothermal solution to be used as a chemical geothermometer.

The correlation of predicted temperature values and the silica content (see table 1) is shown in fig. 4.

A nonlinear smooth increase of the temperature from around 80 until 140 °C takes place in this figure without spikes. It could be a result of carefully collected water samples and their processing in laboratory conditions.

The Na–K geothermometers require using the respective ratio of these two cations, which is shown in the fig. 5. This plot demonstrates uneven distribution of this ration. Triangles in the upper right corner correspond to the most of samples collected from the samples Nos. ES2, ES3, ES6–ES11, ES15, ES 28. Triangle concentrated in the left lower corner were received for the rest of tested water samples. Despite this specific distribution of Na/K, using this geothermometer gives rather smooth ralationship between the Na/K ratio and the calculated temperature, fig. 6. The temperature estimated using this geothermometer ranges from around 250 until 360 °C, which is higher than values received using the silica geothermometer.

The temperature calculated from the Na/K ratio regularly reduces when the Na/K decreases in a regular way as shown in the fig.6. Temperature values estimated using the silica and Na/K geothermometers considerably differ. Other researchers reported this feature also. Several water samples taken from the Sarein area were studied earlier [21] by silica (T_q, °C), Na/K and Na–K–Ca and other geothermometers, table 2. In general the results from the table 2 and table 1 correlate concerning the area of Sarein hot springs, though the data on studied water samples (their exact localities, laboratory conditions for analysis of these samples, etc. in table 2) are not described in this publication and they may slightly differ of those, included into the table 1. All three geothermometers show considerable differences in predicted temperatures, but all they exceed 100 °C.

The Na/K geothermometer gives much higher temperatures. The highest difference is observed between results obtained using the silica and Na/K geothermometers systematically exceeding 100 °C.

Silica geothermometry applied to warm spring waters is not likely to give higher temperatures than 230–250 °C because quartz dissolves and precipitates very quickly in response to changing temperature at ~ 230 °C [21, 22].

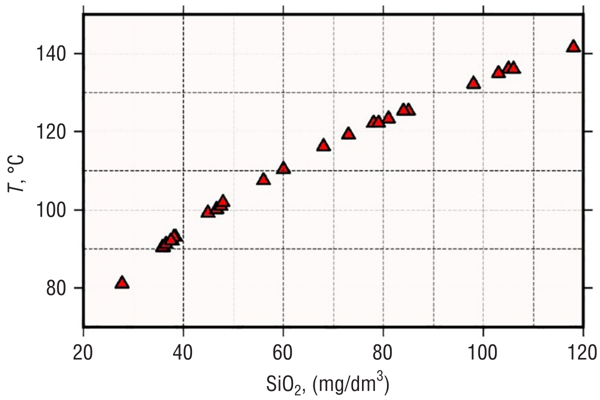

Fig. 4. SiO_2 content in water samples and calculated temperature

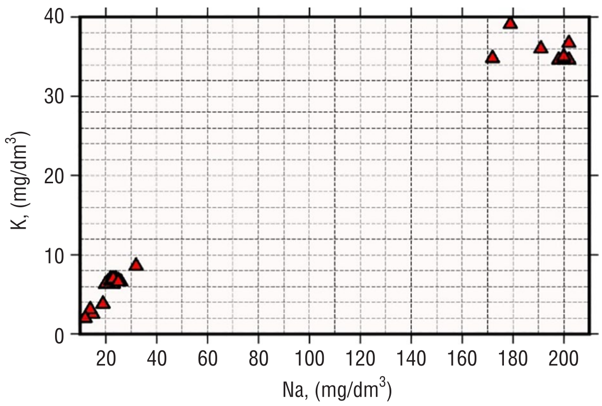

Fig. 5. Na/K ratio plot

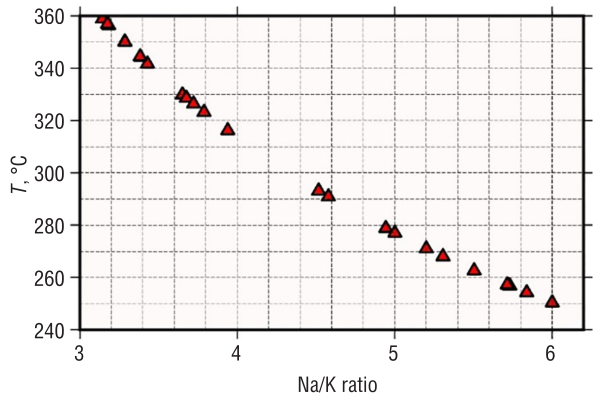

Fig. 6. Temperature estimated from the ratio of lithophilic elements Na/K

Table 2. **Results for silica and cation geothermometers for thermal springs in the Sarein locality of the Mount Sabalan (derived from [21])**

Area	Sample No.	T_q, °C	*T*, Na/K, °C	*T*, Na–K–C, °C
Sarein	1001	138	305	193
Sarein	1004	139	274	210
Sarein	1007	139	299	215
Sarein	1009	127	285	182
Sarein	1010	110	274	216

6. Conceptual model. The reservoir rocks of the geothermal system to the east of Sabalan consist generally of volcanic units that were subjected to intense fracturing imposed by the tectonic stress. The fracturing provided suitable secondary permeability and facilitated the upward migration of high-temperature geothermal fluids (fig. 7). The high-temperature chloride-bearing ascending fluids reach the surface as geothermal springs in the Sarein area. There are also hot spring waters of carbonate composition generated from condensation of the ascending CO_2-rich steam by low-O_2 underground waters in this area. In the northern parts of the studied areas (the Sardabeh and the Yediboloug), the composition of spring waters is different, and have chiefly acid-sulfate nature resulting from oxidation of sulfides by high O_2 content in underground waters. Based upon geothermometric calculations, the geothermal reservoirs in these areas have a temperature range of 150–250 °C. Field observations revealed that the principal water feeding areas are located around the Sabalan caldera, which is covered permanently by glaciers and snow throughout the year. The melted water in the area percolates deep into the ground through existing numerous fault and cracked zones around the caldera.

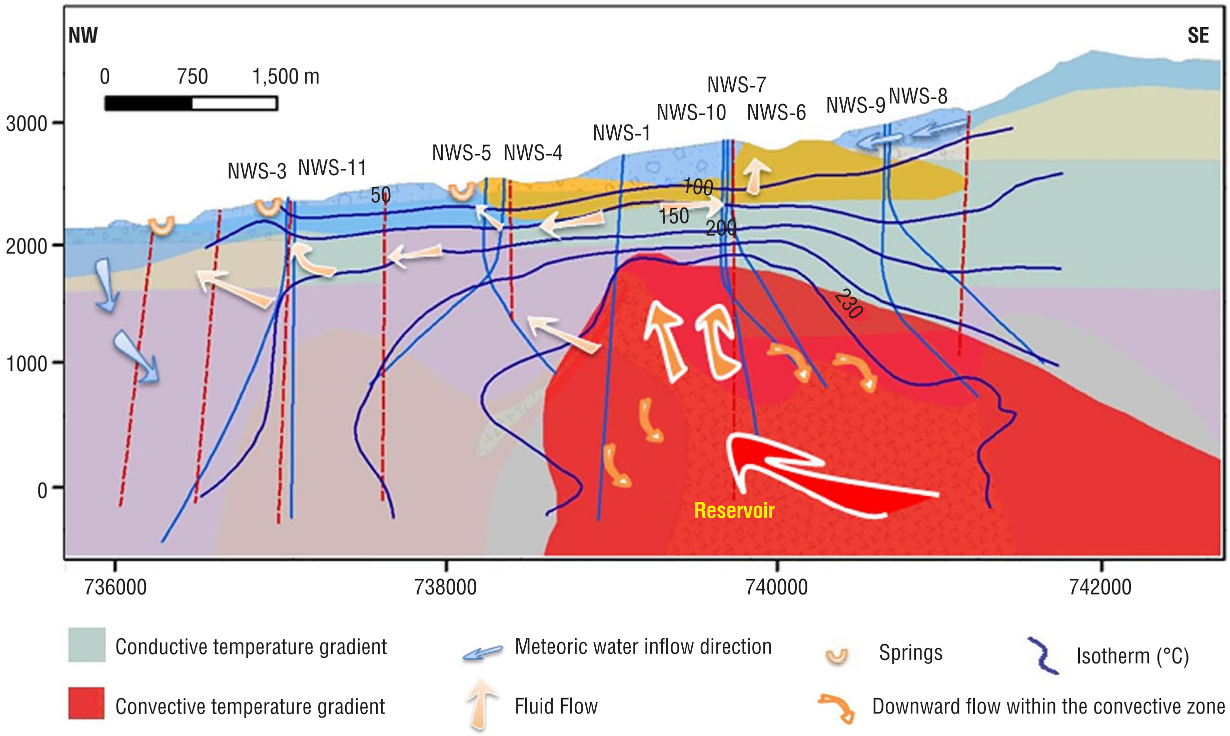

Fig. 7. Geologic-geothermal crossection through several prospecting well of the NW part of the Mount Sabalan [31]

Temperature values recorded in the logging process in several prospecting wells drilled in the NW part of the Mount Sabalan reach 150–250 °C. An example of the temperature variation with depth is shown in fig. 8 for the NWS-3 well for different shut-down time from 40 days till 5 months, fig. 8.

The recorded temperature reaches up to 300–350 °C at depth exceeding 2000 – 2500 m. These values are compatible with the temperature data shown in the table 1 as we assume that the Sabalan has same magma source for the whole area of the volcano. The temperature values calculated using two considered geothermometers can differ also depending on the depth of the origin of hot springs discharged water to the ground surface. It is possible to assume that lithophile elements Na and K were dissolved in water at deeper layers and then migrating upwards to rocks with lower temperature enriched in silica. Then a mixture of these waters discharges to the ground surface. It will result in lower temperatures predicted using the silica thermometer and higher for Na/K based geothermometer. This possible mechanism requires further investigations.

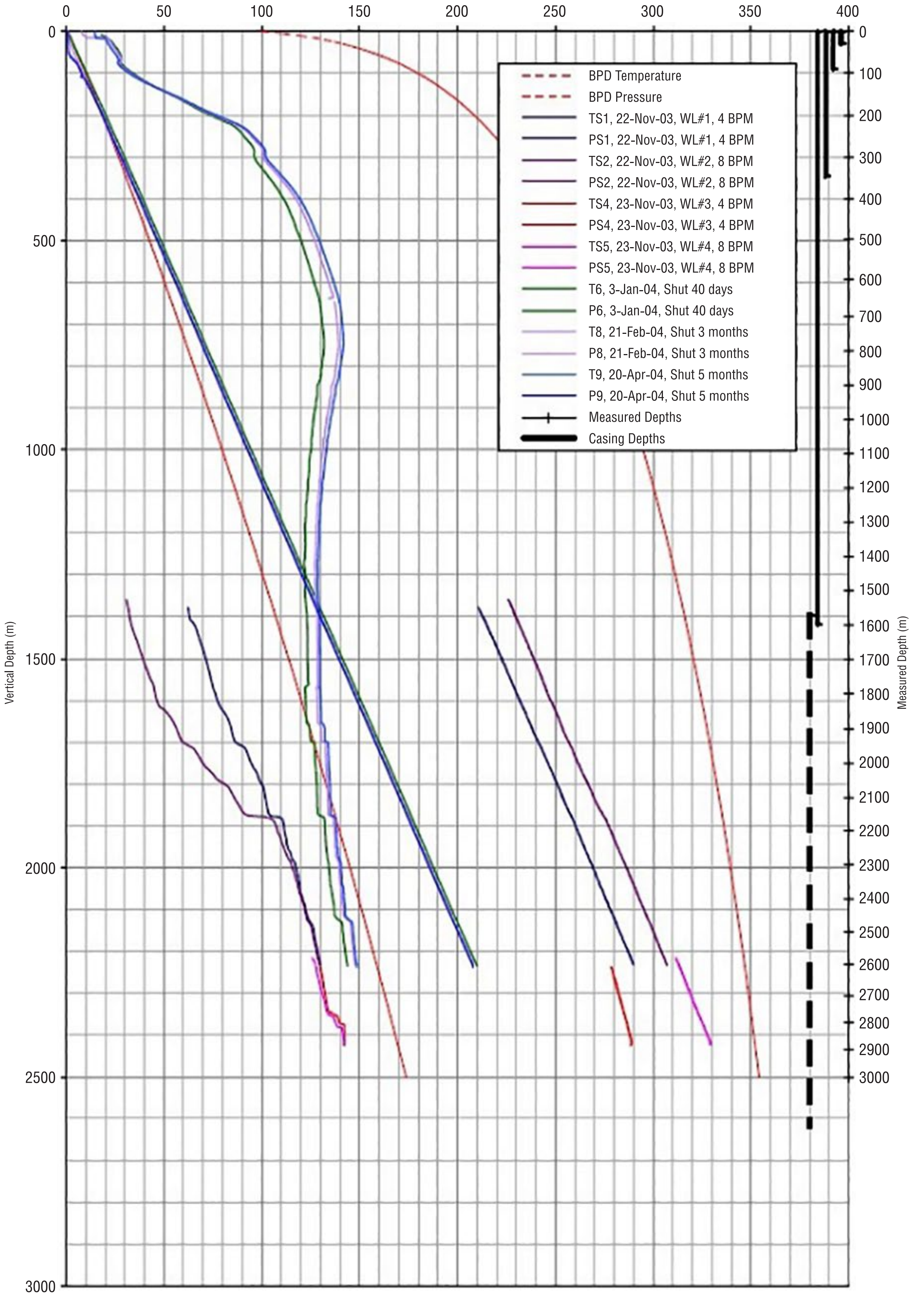

Fig. 8. Temperature-depth logs for the NWS-3 well for different shut-down time [32]

Conclusions. 1. Geological considerations east of the Mount Sabalan indicate that the calc-alkaline volcanic-sedimentary units constitute the great volume of the geothermal reservoir in the study district. Rocks suffered argillic alteration act as cap rocks for this reservoir. In some localities of the study district siliceous (chalcedony and opal) sinters developed around orifices of hot springs. The NW–SE trending faults played an important role in the development of these hot springs.

2. The geothermal fluids in the study district, in terms of physico-chemical parameters, have characteristics that differ from those of other geothermal fields around Mount Sabalan, particularly in the southern and northwestern districts.

3. The information on the dissolved silica concentration and the Na/K ratio in a hydrothermal solution can be used as chemical geothermometers.

4. The geothermal system to the east of Sabalan could be considered as an important area for geothermal steam extraction for production of “geothermal” electricity in future.

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