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Geochemistry of hydrothermally altered rocks from Los Azufres geothermal field, Mexico

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RESUMEN

Estudios cualitativos y semicuantitativos fueron realizados para profundizar en el conocimiento de los efectos impuestos por la alteración hidrotermal en las rocas volcánicas del campo geotérmico de Los Azufres (Michoacán, México). Estos estudios incluyeron el análisis químico por fluorescencia de rayos X de muestras de canal y núcleos, provenientes de los pozos Az-3, Az-26 y Az-52 a diferentes profundidades. Con estos análisis se estudió una secuencia volcánica de 2000 m de espesor. Las rocas volcánicas estudiadas forman una secuencia calco-alcalina cuya composición varía de la basáltica a la riolítica. La comparación de la composición química de las rocas alteradas por los procesos hidrotermales, con aquélla de las rocas frescas (muestreadas en la superficie), muestra una movilidad elemental relativamente baja. El cálculo simple de pérdida y ganancia de elementos indica una silicificación débil, así como una movilidad baja de álcalis.

PALABRAS CLAVE: Sistemas geotérmicos, alteración hidrotermal, movilidad de elementos, Cinturón Volcánico Mexicano.

ABSTRACT

Qualitative and semi-quantitative studies of element mobility at Los Azufres geothermal field, Michoacán, Mexico, were carried out, in order to get a better understanding of the hydrothermal alteration processes that affected the volcanic rocks from this area. X-ray fluorescence techniques were applied to analyse well cuttings and drill cores from wells Az-3, Az-26 and Az-52 at different depths. With these analyses a 2000-m thick volcanic sequence was recorded. Geochemically these rocks form a calc-alkaline trend from basaltic to rhyolitic composition. Comparing the chemical composition of altered samples with that of "fresh" samples from the surface we find relatively low element mobility during alteration. Simple calculations of element loss and gain indicate a weak silicification and low mobility of alkalis.

KEYWORDS: Geothermal systems, hydrothermal alteration, element mobility, Mexican Volcanic Belt.

INTRODUCTION

Interaction of high-temperature fluids with rocks in hydrothermal systems produces mineralogical and geochemical changes in "fresh" rocks. The mobility of major elements is controlled by three main factors (Rollinson, 1993): the stability and composition of the minerals in the unaltered rock, the stability and composition of the minerals in the alteration product, and the composition, temperature, and volume of the fluid phase. Element mobility in rocks can be evaluated, provided that initial ("fresh") and final (altered) rock compositions are known. However, in many cases, the "fresh" rock is no longer available for comparison, especially in paleo-hydrothermal systems or in systems where the alteration affected the whole geological unit. Given the fairly small range in chemical composition of many volcanic rocks, the unaltered compositions can, however, be estimated reasonably well. The geothermal field Los Azufres, Michoacan, Mexico, exemplifies such a case.

In order to study the chemical changes imposed onto the volcanic rocks from Los Azufres as a result of the water-rock interaction, chemical analyses of whole rock samples were done using X-ray fluorescence technique. The purposes of this study were to obtain a better understanding of the water/rock interaction processes occurring in the field and to make an attempt to quantify element mobility, despite the lack (at some known depths in the field) of the "fresh" rock for comparison.

GEOLOGICAL SETTING

Los Azufres is one of several Pleistocene silicic volcanic centres with active geothermal systems in the Mexican Volcanic Belt (MVB, Aguilar y Vargas and Verma, 1987). It is located approximately 200 km northwest of Mexico City. With an electricity production of 98 MW, it represents the second most important geothermal field in Mexico (Quijano León and Gutiérrez Negrín, 1995).

The volcanic rocks at Los Azufres have been described by different authors (Cathelineau *et al.*, 1987; De la Cruz *et al.*, 1982; Dobson and Mahood, 1985; Huitrón Esquivel and Franco Serrano, 1986; López Hernández, 1991; Razo Montiel *et al.*, 1989). Geologically, two principal divisions can be distinguished (Figure 1):

(1) a silicic sequence of rhyodacites, rhyolites and dacites with ages between 1.0 and 0.15 m.y. and a thickness up to 1000 m (Dobson and Mahood, 1985). According to Razo Montiel *et al.* (1989), five different units can be differentiated: *Agua Fría* rhyolite, *Tejamaniles* dacite, *Cerro Mozo* and *San Andrés* dacites and *Yerbabuena* rhyolite. This sequence serves as a seal to the aquifer from the surface, allowing the geothermal system to pressurise.

(2) a 2700 m thick interstratification of lava flows and pyroclastic rocks, of andesitic to basaltic composition with ages between 18 and 1 m.y., forming the local basement (Dobson and Mahood, 1985). This unit provides the main aquifer with fluid flow through fractures and faults, sometimes reaching the surface.

Three different fault systems, which confer secondary permeability to the geological units, can be distinguished in the field (Garduño Monroy, 1985; Garduño Monroy, 1988): NE-SW, E-W and N-S. The E-W system is the most important one for geothermal fluid circulation. Geothermal manifestations (fumaroles, solfataras and mudpits), geophysical anomalies and important energy production zones are related to this fault system.

The thermal fluids are sodium-chloride-rich waters with high CO_2 and H_2S contents, and a pH around 7.5 (Moreno Ochoa, 1989). Average Cl^- contents are 3100 mg/kg and CO_2 can represent as much as 90% of the total gas phase. Fluid temperatures can reach values as high as 320ºC, however 240 to 280ºC are normal in the field.

As origin for the hydrothermal system Iglesias *et al.* (1985) suggest a deep, homogeneous, over the whole field extended (paleo) aquifer. However some important regional differences can be at present noted. In the northern part of the field (Marítaro zone) the geothermal fluids are formed by a mixture of gases and liquid, with T around 300 to 320ºC. In the south (Tejamaniles zone) the gas phase generally dominates over the liquid phase (weight %) and temperatures are lower than in the north (260-280ºC). Regional permeability and system pressure differences, as well as different boiling rates may be the reason for these divergences.

Hydrothermal alteration has affected most rocks in the geothermal field to varying extent. Studies of hydrothermal alteration at Los Azufres have been carried out, among others, by Cathelineau *et al.* (1985), González Partida *et al.* (1989) Robles Camacho *et al.* (1987) and Torres-Alvarado (1996). These studies have shown that partial to complete hydrothermal metamorphism has occurred with mineral paragenesis from greenschist to amphibolite facies (Cathelineau *et al.*, 1985). Most important alteration assemblages are with increasing depth: argillitization/ silicification, zeolithe/calcite formation, sericitization/ chloritization, chloritization/epidotization. For a complete description of alteration characteristics see Cathelineau *et al.* (1985) and Torres-Alvarado (1996).

SAMPLES AND METHODOLOGY

Drill cuttings and cores from different depths of the wells Az-3, Az-26 and Az-52 (Figure 1) were used. The well Az-26 (1241 m in depth) penetrates the complete volcanic sequence. It cuts the first 500 m of interlayered rhyolites and dacites (from here on called felsic rocks) and andesites down to the bottom. The wells Az-3 (2450 m in depth) and Az-52 (1936 m in depth), were completely drilled through andesites (referred to as mafic rocks below).

Major and trace elements concentrations were determined by the X-ray fluorescence (XRF) technique on duplicate fused discs at the Institut für Mineralogie, Petrologie und Geochemie, Tübingen University, Germany (Table 1). The X-ray spectrometer used for these analyses was a Siemens SRS-300, using a Rh-source. Routine precision is reported in Table 1.

Bulk specific gravity G, (using the picnometer method) and loss on ignition (LOI) were determined in duplicate for all samples. Both parameters are reported in Table 2, together with an approximate amounts of alteration, on the basis of relative amounts of secondary (hydrothermally formed) minerals compared to primary phases observed petrographically.

Quantification of element mobility is in Los Azufres a rather difficult task, due to the following reasons:

(1) A direct, unequivocal comparison between "fresh" and altered rocks is not possible, because of the lack of both samples from the same horizon. For an application of this methodology see Verma (1992).

(2) Calculations of element mobility by means of mass balances, as proposed by Gresens (1967) should be used with caution, because volume changes during alteration can not be discarded.

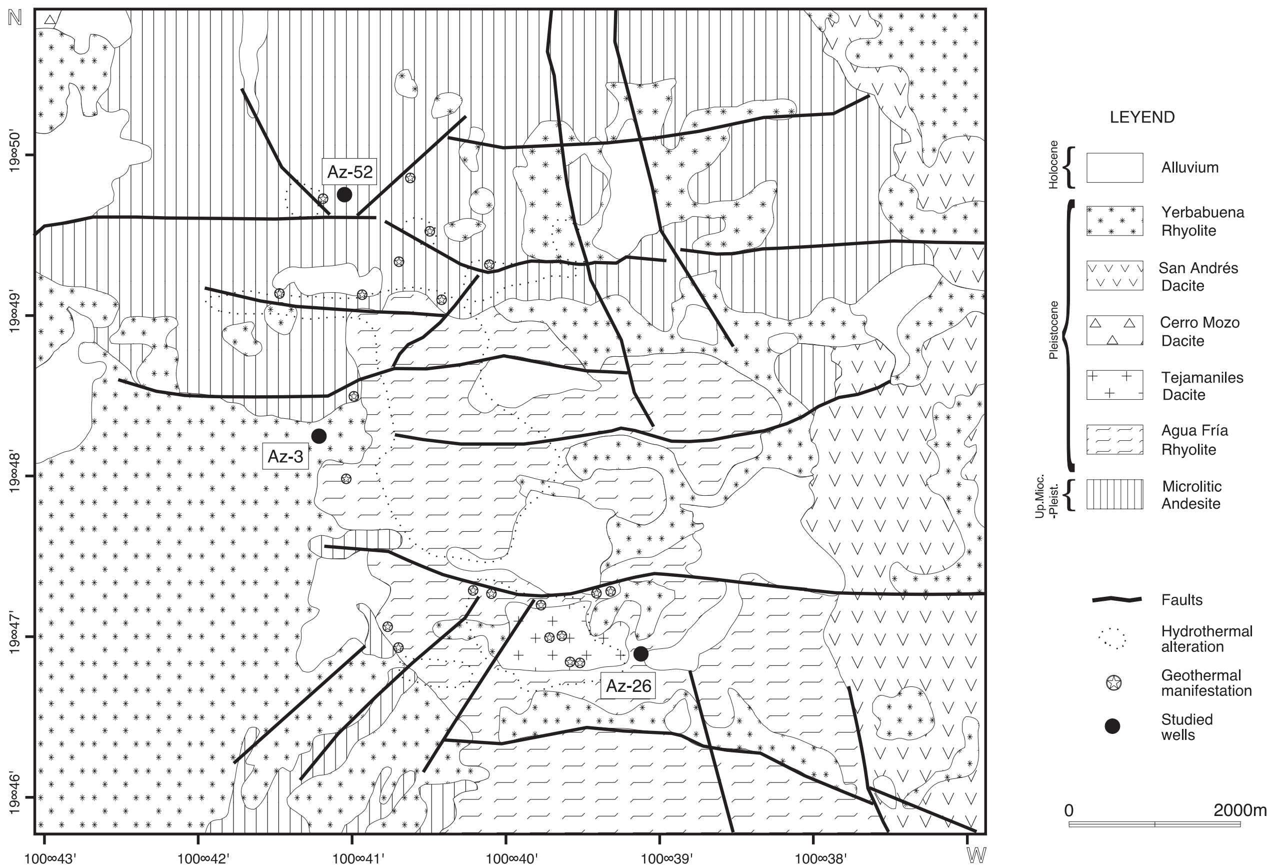

Fig. 1. Geological map of the Los Azufres geothermal field (modified after Razo Montiel *et al.*, 1989). Filled circles indicate the studied wells.

(3) Quantification of element mobility based on the assumption that one or more elements remain immobile during alteration is uncertain, because the elements that are typically considered as being immobile in the literature show large variations in rocks from Los Azufres. For example, Ti contents are high compared to similar volcanic rocks; Al shows large variations in concentration within analysed samples and it is an important element forming hydrothermal mineral phases. Zr was not reported for all “fresh” rocks analyses, making it impossible to assess the Zr mobility in the field.

As absolutely unaltered samples are not available, comparisons can be made only (1) to the least altered samples retrieved for any single lithology, or (2) against some “fresh” rocks taken from within the field, but which would not correspond exactly to the same horizon of the altered one.

In an attempt to calculate element mobility in altered rocks at Los Azufres, specific gravity determinations were made on all of the analysed samples, enabling representation of the bulk chemistry on a mass per volume basis. Calculations of the mass (of any single element) mobilised during alteration is obtained by subtracting the relevant oxide abundance of the least altered sample from each of the more altered samples. The values are negative for samples that lost mass during the alteration and positive for those which gained mass.

The results of the elemental gain/loss calculations are reported in Table 2. Because of the large amount of samples, it is convenient to separate the chemical analyses of rocks into groups of similar composition. Element mobility was calculated (1) for felsic rocks (Table 2.1); (2) for mafic rocks having a SiO_2-content lower than 60 wt. % (Table 2.2) and (3) for mafic rocks with more than 60 wt. % SiO_2 (Table 2.3). For the felsic rocks, the sample from Az-26 at 20 m depth was considered representative for the “fresh” rocks, due to its low degree of alteration. For the first mafic group (SiO_2 < 60 wt. %), the “fresh” rock used for comparison was an average of samples PDLA82-37 (Dobson and Mahood, 1985), LAS 06, A9 1600 and A9 2359 (Cathelineau *et al.*, 1987). For the second group (SiO_2>60 wt.%), samples AUM5,

Table 1

Whole rock geochemical data of hydrothermally altered rocks from Los Azufres geothermal field. Sample names designate the well number and depth. Major element concentrations in wt. %, trace element concentrations in ppm.

Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Ba	Cr	Nb	Ni	Rb	Sr	V	Y	Zn	Zr	LOI	Total
3-098	61.31	1.14	16.64	5.52	0.11	1.13	4.59	3.83	2.35	0.23	676	0	11	5	65	450	102	24	80	241	2.48	99.49
3-200	57.75	1.36	17.39	7.39	0.09	1.01	3.72	2.98	1.62	0.25	519	31	13	9	55	391	111	25	87	255	3.54	97.25
3-298	58.43	1.14	16.66	7.02	0.09	1.65	4.89	2.82	1.43	0.24	508	66	12	33	66	454	118	26	73	210	3.26	97.78
3-398	52.45	1.72	19.03	10.76	0.07	2.54	3.74	2.28	0.69	0.19	253	175	10	62	25	327	199	24	65	191	6.70	100.30
3-502	58.91	0.80	15.08	5.40	0.09	2.54	5.39	2.24	1.40	0.14	348	66	7	36	59	415	157	22	67	182	6.92	99.04
3-598	56.78	0.84	14.36	4.97	0.11	3.37	6.89	2.20	1.82	0.13	298	49	5	29	64	561	128	20	58	184	7.29	98.89
3-700	58.16	0.78	15.35	5.07	0.09	4.03	6.91	1.87	1.06	0.14	303	90	7	35	43	350	101	21	55	181	6.04	99.60
3-806	56.73	0.99	15.46	5.54	0.10	2.87	6.60	2.31	2.21	0.21	436	51	6	30	62	545	132	25	60	217	3.71	96.89
3-900	61.12	0.84	15.54	5.17	0.07	2.18	4.91	1.89	3.60	0.16	353	73	6	36	117	406	130	23	49	169	2.56	98.17
3-998	57.26	0.98	15.27	5.68	0.09	4.54	6.83	2.62	1.82	0.27	390	99	6	75	35	832	129	18	58	192	2.25	97.79
3-1102	60.44	0.83	15.62	5.14	0.07	2.45	5.94	3.46	1.68	0.21	486	68	1	27	57	916	104	18	55	163	2.05	98.08
3-1202	60.63	0.81	15.44	5.32	0.09	3.52	5.57	2.54	2.09	0.17	391	74	5	28	58	590	109	21	61	182	2.22	98.55
3-1300	58.77	0.80	16.63	5.50	0.10	3.47	6.18	3.04	1.12	0.21	317	37	4	26	34	747	96	19	63	156	2.24	98.19
3-1400	62.46	0.69	16.41	4.59	0.09	2.07	5.55	3.50	1.83	0.17	383	25	2	9	53	929	98	17	61	125	1.64	99.17
3-1498	56.63	0.95	17.62	6.12	0.09	3.54	7.17	3.24	1.19	0.21	390	18	4	4	27	831	163	20	67	164	2.02	98.95
3-1602	55.18	0.78	17.47	6.83	0.10	2.70	9.13	3.44	0.50	0.16	260	91	5	20	17	672	136	21	55	148	2.36	98.77
3-1700	57.15	0.82	15.36	5.49	0.08	4.72	5.10	3.98	1.06	0.14	244	100	4	21	34	487	134	20	62	145	2.48	96.49
3-1800	54.06	1.01	16.97	6.95	0.11	3.93	7.75	2.93	1.40	0.18	342	60	4	12	30	571	186	21	69	129	1.58	97.01
3-1900	55.23	1.15	16.27	7.27	0.13	3.46	7.75	2.53	1.44	0.36	482	74	9	24	35	563	145	26	71	247	2.07	97.82
3-2000	52.56	1.31	14.78	8.09	0.14	4.12	8.31	2.57	0.80	0.41	451	62	13	24	21	598	139	26	83	248	4.47	97.72
3-2100	51.36	1.01	17.35	8.78	0.15	1.94	11.81	2.43	0.56	0.27	195	70	9	17	15	609	169	24	40	153	2.00	97.78
3-2198	55.31	1.15	15.60	7.12	0.09	5.77	7.12	2.90	0.66	0.28	170	191	7	38	19	632	137	23	74	191	3.41	99.55
3-2300	54.21	1.56	15.08	7.92	0.13	4.50	7.58	3.16	0.96	0.41	410	94	13	33	26	566	147	27	80	253	3.65	99.32
3-2380	52.48	1.56	15.09	8.86	0.15	4.06	9.07	2.71	1.43	0.45	503	91	14	37	35	577	147	31	114	257	2.66	98.70
26-20	74.24	0.21	13.97	2.04	0.04	0.16	0.42	2.73	4.35	0.04	244	4	23	8	157	36	18	29	78	178	2.02	100.30
26-60	63.66	0.25	14.54	2.27	0.08	0.31	6.62	3.54	3.24	0.03	553	9	16	15	85	170	25	36	54	186	5.54	100.20
26-120	71.91	0.30	14.28	2.26	0.02	0.26	1.21	4.07	4.15	0.04	573	14	16	3	124	133	18	26	42	191	0.89	99.49
26-180	71.49	0.30	14.05	2.34	0.05	0.35	1.31	3.89	4.27	0.06	569	41	15	1	124	129	18	31	68	208	2.07	100.29
26-220	74.40	0.14	13.72	1.76	0.01	0.03	0.37	4.12	4.51	0.03	589	3	23	9	126	30	8	21	46	278	1.20	100.40
26-280	74.76	0.13	14.07	0.87	0.01	0.03	0.40	3.88	4.32	0.00	495	0	23	0	120	29	5	19	27	292	1.72	100.28
Std. Dev.		0.39	0.02	0.17	0.24	0.00	0.13	0.11	0.07	0.04	0.01	29	10	4	8	5	8	6	3	6	12	
Det. Lim.		0.74	0.04	0.30	0.42	0.01	0.23	0.19	0.13	0.07	0.02	51	17	7	13	9	13	10	4	12	21	

AUM 11 (Aumento and Gutiérrez Negrín, 1980) and LAS 07, A9 2288 and A9 1440 (Cathelineau *et al.*, 1987) were averaged.

The rock sample chosen as "fresh" was assumed to be representative of all geochemically similar rocks belonging to the volcanic sequence. It is likely that there may be small but systematic variations in major elements amongst different units. However, this work attempts to identify the obvious and persistent alteration trends, which stand apart from such systematic variations.

RESULTS AND DISCUSSION

Figure 2 shows the chemical composition of the analysed rocks. "Fresh" samples as reported in the literature have been plotted as well. In the AFM diagram most samples fall along a systematic trend in the field of calc-alkaline rocks,

Table 1 (Cont.)

Whole rock geochemical data for the hydrothermally altered rocks from Los Azufres geothermal field. Sample names designate the well number and depth. Major element concentrations in wt. %, trace element concentrations in ppm.

Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Ba	Cr	Nb	Ni	Rb	Sr	V	Y	Zn	Zr	LOI	Total
26-340	72.45	0.12	13.66	1.10	0.01	0.03	0.42	4.61	4.52	0.02	530	2	21	1	124	26	5	31	41	281	0.45	97.49
26-380	72.10	0.11	12.56	1.36	0.04	0.08	1.29	2.21	3.97	0.01	340	0	18	8	141	70	5	36	60	238	4.50	98.30
26-440	74.70	0.13	12.78	1.63	0.06	0.09	0.43	2.90	4.94	0.03	340	14	21	2	134	44	7	34	60	221	2.13	99.90
26-480	76.40	0.10	12.52	1.00	0.01	0.03	0.33	3.17	4.43	0.03	316	12	19	0	116	16	5	32	60	234	1.58	99.67
26-540	60.82	1.17	16.55	6.27	0.12	1.43	4.01	2.84	2.02	0.27	435	36	13	22	54	339	107	25	66	211	4.74	100.37
26-620	51.00	1.83	17.20	9.31	0.15	2.91	7.80	3.70	1.27	0.36	383	78	14	55	26	550	180	26	89	207	4.52	100.22
26-700	59.57	1.52	14.15	6.79	0.10	2.43	5.75	2.44	1.57	0.30	435	42	9	19	38	406	156	22	74	176	5.17	99.94
26-740	57.22	0.69	14.56	4.25	0.06	3.50	5.43	3.27	2.03	0.12	417	110	5	27	61	427	89	21	48	197	4.44	95.71
26-780	58.05	1.07	14.92	5.84	0.08	3.21	4.68	2.38	1.84	0.18	389	102	7	45	56	393	124	23	68	206	5.37	97.76
26-800	58.98	0.85	15.03	5.60	0.10	3.75	5.39	2.70	1.41	0.15	319	91	6	35	48	500	123	19	65	165	6.83	100.92
26-840	58.91	0.97	14.82	6.21	0.08	3.83	4.36	2.72	1.78	0.18	343	96	9	33	59	336	136	24	73	197	6.13	100.12
26-940	54.04	0.75	14.51	5.22	0.12	4.68	7.81	2.42	1.53	0.16	234	69	5	28	41	511	109	18	64	150	9.03	100.40
26-1000	62.96	0.73	13.55	4.42	0.07	2.45	4.24	2.21	2.04	0.16	281	54	10	24	60	458	103	22	60	186	5.38	98.33
26-1080	61.48	0.79	14.48	5.00	0.07	3.10	4.81	2.54	2.00	0.19	316	116	5	34	62	546	110	21	69	169	5.32	99.92
26-1160	52.33	0.85	16.40	6.91	0.12	5.61	8.70	2.34	0.80	0.13	222	243	3	84	22	441	150	18	69	105	6.06	100.38
52-60	61.24	1.09	17.37	5.89	0.09	2.03	5.24	3.56	2.38	0.23	619	4	10	0	56	474	108	24	76	227	1.31	100.58
52-100	61.18	1.10	17.00	6.01	0.08	1.93	5.01	3.27	2.38	0.27	598	8	10	0	60	454	105	26	74	224	2.08	100.47
52-200	59.22	1.26	18.18	7.60	0.09	2.26	4.12	2.24	1.10	0.32	437	18	11	0	38	367	107	26	89	248	4.03	100.57
52-220	60.84	1.23	18.08	6.39	0.07	1.56	4.73	3.46	1.56	0.32	555	2	10	1	48	449	115	24	87	243	2.44	100.84
52-300	52.53	1.48	18.00	8.19	0.12	2.36	7.06	3.12	1.09	0.33	421	19	10	32	25	618	143	27	87	215	3.96	98.40
52-380	52.15	1.39	17.69	8.03	0.13	3.27	8.14	3.74	0.68	0.31	287	111	8	46	19	577	164	24	84	175	4.47	100.14
52-420	60.53	0.86	16.51	5.35	0.09	2.45	6.58	3.11	1.03	0.18	383	60	6	27	29	520	86	17	64	164	4.02	100.84
52-520	68.16	0.42	13.81	3.30	0.05	1.97	3.28	3.54	3.73	0.09	510	72	9	33	91	212	45	18	44	145	1.68	100.14
52-600	70.11	0.41	14.31	3.27	0.04	1.19	2.20	3.57	3.97	0.08	541	48	10	11	101	189	46	18	43	148	1.23	100.49
52-620	70.86	0.36	13.82	2.91	0.04	1.08	1.82	3.68	4.12	0.04	563	36	8	12	100	169	41	19	44	139	1.25	100.09
52-720	58.11	0.88	17.33	5.39	0.09	3.83	6.76	2.90	1.61	0.16	390	96	7	38	35	489	103	18	66	141	2.89	100.09
52-820	56.27	0.99	17.99	5.77	0.11	3.84	6.07	3.74	1.15	0.19	364	109	7	25	39	523	110	17	72	145	4.07	100.33
52-940	58.95	1.05	15.79	6.41	0.10	2.30	6.44	3.11	2.12	0.27	435	105	8	37	67	435	107	22	66	177	3.32	100.00
52-1080	60.29	0.84	16.12	5.63	0.08	3.05	5.90	2.58	2.81	0.18	470	74	4	25	81	487	130	19	68	164	2.24	99.85
52-1120	60.54	0.86	16.02	5.18	0.08	2.82	5.41	3.50	2.25	0.18	435	80	4	23	59	540	117	23	62	192	3.08	100.07
52-1180	58.12	0.75	15.61	5.10	0.12	2.34	6.92	2.88	2.10	0.14	414	100	3	18	55	731	82	16	52	127	2.20	96.44
52-1220	60.91	0.86	16.11	5.60	0.07	4.03	5.36	3.01	1.71	0.19	399	131	5	23	52	667	127	18	63	156	2.33	100.32
52-1320	60.14	0.75	16.13	5.16	0.09	3.72	5.42	4.61	2.31	0.21	406	133	0	58	47	838	110	14	59	134	1.58	100.29
52-1400	58.27	0.88	16.51	5.33	0.09	3.94	5.90	3.03	1.54	0.24	330	97	3	19	40	861	113	22	63	185	2.55	98.45
52-1480	61.23	0.75	16.05	4.80	0.08	2.77	6.53	3.17	2.54	0.14	482	101	5	18	66	483	101	22	156	191	2.11	100.32
52-1600	62.22	0.78	15.79	5.10	0.08	2.94	5.05	3.88	2.52	0.17	449	93	6	20	70	494	117	21	54	176	1.90	100.58
52-1640	60.08	0.86	16.06	5.67	0.10	4.03	4.51	4.74	2.12	0.19	449	120	5	28	57	512	138	21	64	169	2.08	100.58
52-1680	61.54	0.69	15.08	4.79	0.08	2.80	5.51	2.79	1.91	0.15	471	147	5	14	54	586	96	21	133	167	2.18	97.69
52-1780	61.68	0.72	16.17	4.88	0.08	3.19	6.14	3.63	1.73	0.19	445	178	6	15	43	647	96	19	69	177	2.02	100.62
52-1860	61.37	0.72	15.72	5.46	0.09	2.91	6.03	3.77	1.89	0.16	444	106	3	18	47	591	99	18	64	170	2.11	100.35
52-1900	61.62	0.74	16.84	4.77	0.08	2.40	5.95	4.01	1.73	0.19	425	44	4	5	43	723	98	19	65	186	1.69	100.17
52-1920	61.69	0.74	17.12	4.72	0.08	2.57	5.24	4.40	1.66	0.21	456	65	5	7	40	710	89	18	87	188	1.78	100.37
Std. Dev.	0.39	0.02	0.17	0.24	0.00	0.13	0.11	0.07	0.04	0.01	29	10	4	8	5	8	6	3	6	12		
Det. Lim.	0.74	0.04	0.30	0.42	0.01	0.23	0.19	0.13	0.07	0.02	5	17	7	13	9	13	10	4	12	21		

Table 2.1

Element mobility calculations of the hydrothermally altered rocks from Los Azufres geothermal field. Group 1: felsic rocks. Sample names designate the well number and depth.

Sample	Alteration	SiO_2	TiO_2	Al_2O_3	$Fe_2O_3^*$	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total	Sp. Grav.
26-20	0	74.24	0.21	13.97	2.04	0.04	0.16	0.42	2.73	4.35	0.04	2.02	100.23	2.73
26-120	11	71.91	0.30	14.28	2.26	0.02	0.26	1.21	4.07	4.15	0.04	0.89	99.38	2.89
26-180	10	71.49	0.30	14.05	2.34	0.05	0.35	1.31	3.89	4.27	0.06	2.07	100.17	2.65
26-280	15	74.76	0.13	14.07	0.87	0.01	0.03	0.40	3.88	4.32	0.00	1.72	100.18	2.84
26-340	15	72.45	0.12	13.66	1.10	0.01	0.03	0.42	4.61	4.52	0.02	0.45	97.39	2.83
26-440	31	74.70	0.13	12.78	1.63	0.06	0.09	0.43	2.90	4.94	0.03	2.13	99.82	2.79
26-480	15	76.40	0.10	12.52	1.00	0.01	0.03	0.33	3.17	4.43	0.03	1.58	99.59	2.84

26-20 was chosen as the fresh sample for comparison purposes.

Mass per volume (kg/m^3)

Sample	Alteration	SiO_2	TiO_2	Al_2O_3	$Fe_2O_3^*$	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI
26-20	0	2022.25	5.82	380.59	55.55	0.97	4.37	11.56	74.43	118.47	0.97	55.02
26-120	11	2091.20	8.75	415.35	65.63	0.55	7.49	35.10	118.24	120.78	1.02	25.88
26-180	10	1891.17	7.86	371.79	61.81	1.23	9.15	34.68	102.94	112.90	1.71	54.76
26-280	15	2119.43	3.60	398.95	24.52	0.20	0.96	11.28	109.88	122.41	0.00	48.76
26-340	15	2105.48	3.52	396.81	32.02	0.26	0.78	12.06	133.85	131.44	0.70	13.08
26-440	31	2087.91	3.68	357.07	45.56	1.71	2.64	12.03	80.95	138.12	0.80	59.54
26-480	15	2178.65	2.95	356.97	28.40	0.26	0.81	9.51	90.41	126.26	0.71	45.06

Mobilised mass (kg/m^3)

Sample	Alteration	SiO_2	TiO_2	Al_2O_3	$Fe_2O_3^*$	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI
26-20	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26-120	11	68.95	2.94	34.76	10.08	-0.41	3.12	23.54	43.81	2.31	0.05	-29.14
26-180	10	-131.09	2.04	-8.80	6.26	0.26	4.78	23.12	28.51	-5.57	0.74	-0.26
26-280	15	97.18	-2.22	18.36	-31.03	-0.77	-3.41	-0.28	35.45	3.94	-0.97	-6.26
26-340	15	83.22	-2.30	16.23	-23.53	-0.71	-3.59	0.50	59.42	12.96	-0.27	-41.94
26-440	31	65.66	-2.14	-23.51	-9.99	0.74	-1.73	0.47	6.52	19.65	-0.17	4.51
26-480	15	156.40	-2.86	-23.62	-27.15	-0.71	-3.56	-2.05	15.99	7.79	-0.25	-9.96
	Average	56.72	-0.76	2.24	-12.56	-0.27	-0.73	7.55	31.62	6.85	-0.15	-13.84

similar to that observed in other regions within the MVB (Cathelineau *et al.*, 1987; Venegas *et al.*, 1985). Based on the SiO_2 and K_2O contents (Figure 2) the rocks of this study trend from basalt to high K-rhyolite, in which nearly all mafic rocks occupy the medium K-field (Gill, 1981). Most mafic rocks from the wells show a lower K_2O content of about 1 wt. %, as referred to unaltered samples. This can be explained by the high mobility of potassium during alteration processes (Rollinson, 1993). However, the general lithological classification is not significantly changed.

This chemical classification for the volcanic rocks from Los Azufres is confirmed by the classification by Winchester and Floyd (1977, Figure 3) based on the basis of Zr and Ti, that is, elements considered less mobile by different authors during hydrothermal alteration processes (e.g. Pearce, 1983). Again a systematic trend from basaltic andesite to rhyolite is observed (Figure 3). Unaltered samples are not shown, because trace elements were analysed for few samples only. Some rocks fall in the trachyandesite field. This may be due to the relatively high amount of Ti in MVB rocks (Gill, 1981)

Table 2.2

Element mobility calculations of the hydrothermally altered rocks from Los Azufres geothermal field. Group 2: mafic rocks with a SiO_2-content < 60 wt.%. Sample names designate the well number and depth.

Sample	Alteration	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total	Sp. Grav.
Fresh[1]	0	58.53	0.87	16.92	5.58	0.11	3.75	6.15	3.60	2.05	0.21	1.41	99.16	2.60
52-200	10	59.22	1.26	18.18	7.60	0.09	2.26	4.12	2.24	1.10	0.32	4.03	100.43	2.60
3-998	15	57.26	0.98	15.27	5.68	0.09	4.54	6.83	2.62	1.82	0.27	2.25	97.60	2.50
3-298	20	58.43	1.14	16.66	7.01	0.09	1.65	4.89	2.82	1.43	0.24	3.26	97.63	2.30
3-200	25	57.75	1.36	17.39	7.39	0.09	1.01	3.72	2.98	1.63	0.25	3.54	97.09	2.70
52-1180	30	58.12	0.75	15.61	5.10	0.12	2.34	6.92	2.88	2.10	0.14	2.20	96.28	2.80
26-700	35	59.57	1.52	14.15	6.79	0.10	2.43	5.75	2.44	1.57	0.30	5.17	99.80	3.00
52-1400	35	58.27	0.88	16.51	5.33	0.09	3.94	5.90	3.03	1.54	0.24	2.55	98.27	3.20
52-940	35	58.95	1.05	15.79	6.41	0.10	2.30	6.44	3.11	2.12	0.26	3.32	99.86	2.80
3-1700	50	57.15	0.82	15.36	5.49	0.08	4.72	5.10	3.97	1.06	0.14	2.48	96.36	2.60
3-700	60	58.15	0.78	15.35	5.07	0.09	4.03	6.91	1.87	1.06	0.14	6.04	99.48	2.40
3-1300	70	58.77	0.80	16.63	5.49	0.09	3.47	6.18	3.04	1.12	0.21	2.24	98.04	2.60
26-800	75	58.98	0.85	15.03	5.60	0.10	3.75	5.39	2.70	1.41	0.15	6.83	100.78	3.05
26-840	75	58.91	0.97	14.82	6.21	0.08	3.83	4.36	2.72	1.78	0.18	6.13	99.99	3.07
26-740	80	57.22	0.69	14.56	4.25	0.06	3.50	5.43	3.27	2.03	0.12	4.44	95.57	2.60
3-502	80	58.90	0.80	15.08	5.40	0.09	2.54	5.39	2.24	1.40	0.14	6.92	98.90	2.40

[1] Average of samples LAS 06, PDLA82-37, A9 1600 and A9 2359 (see text).

Mass per volume (kg/m^3)

Sample	Alteration	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI
Fresh	0	1534.57	22.75	443.70	146.17	2.82	98.32	161.12	94.32	53.68	5.57	36.97
52-200	10	1533.20	32.62	470.67	196.85	2.20	58.58	106.76	57.99	28.45	8.34	104.33
3-998	15	1466.68	25.02	391.15	145.41	2.38	116.18	174.89	67.16	46.49	6.99	57.63
3-298	20	1376.63	26.81	392.45	165.27	2.03	38.83	115.20	66.46	33.78	5.75	76.80
3-200	25	1605.93	37.68	483.63	205.53	2.42	28.11	103.45	82.81	45.19	6.81	98.44
52-1180	30	1690.11	21.72	454.09	148.34	3.58	67.93	201.21	83.72	61.13	4.19	63.98
26-700	35	1790.66	45.84	425.49	204.19	2.95	72.95	172.81	73.43	47.22	9.05	155.41
52-1400	35	1897.56	28.56	537.51	173.46	2.96	128.20	192.12	98.66	50.11	7.82	83.03
52-940	35	1652.88	29.47	442.78	179.65	2.83	64.58	180.47	87.32	59.50	7.43	93.09
3-1700	50	1542.01	22.15	414.32	147.99	2.24	127.22	137.50	107.25	28.49	3.91	66.91
3-700	60	1402.96	18.79	370.26	122.41	2.10	97.13	166.72	44.99	25.55	3.38	145.71
3-1300	70	1558.45	21.22	440.89	145.72	2.52	92.00	163.94	80.51	29.78	5.57	59.40
26-800	75	1784.82	25.57	454.97	169.50	2.91	113.58	163.06	81.59	42.76	4.54	206.70
26-840	75	1808.69	29.87	454.97	190.58	2.58	117.60	133.84	83.48	54.68	5.50	188.21
26-740	80	1556.57	18.85	396.02	115.57	1.71	95.32	147.61	88.99	55.33	3.24	120.79
3-502	80	1429.37	19.49	365.95	130.99	2.18	61.54	130.82	54.38	33.95	3.42	167.92

Mobilised mass (kg/m^3)

Sample	Alteration	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI
Fresh	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
52-200	10	-1.37	9.87	26.97	50.68	-0.62	-39.74	-54.36	-36.34	-25.23	2.76	67.36
3-998	15	-67.89	2.28	-52.55	-0.76	-0.44	17.86	13.77	-27.17	-7.20	1.42	20.66
3-298	20	-157.94	4.06	-51.25	19.09	-0.79	-59.50	-45.92	-27.86	-19.90	0.18	39.83
3-200	25	71.36	14.93	39.93	59.35	-0.40	-70.21	-57.67	-11.51	-8.50	1.24	61.47
52-1180	30	155.54	-1.02	10.39	2.17	0.76	-30.39	40.09	-10.60	7.44	-1.38	27.01
26-700	35	256.09	23.09	-18.21	58.02	0.13	-25.37	11.69	-20.89	-6.46	3.48	118.44
52-1400	35	362.99	5.81	93.81	27.29	0.14	29.88	31.00	4.34	-3.57	2.24	46.07
52-940	35	118.31	6.72	-0.92	33.48	0.01	-33.75	19.35	-7.01	5.82	1.86	56.12
3-1700	50	7.44	-0.59	-29.38	1.82	-0.58	28.89	-23.62	12.93	-25.19	-1.66	29.94
3-700	60	-131.61	-3.95	-73.44	-23.77	-0.72	-1.20	5.60	-49.33	-28.14	-2.19	108.74
3-1300	70	23.88	-1.53	-2.81	-0.45	-0.30	-6.33	2.82	-13.81	-23.90	0.00	22.43
26-800	75	250.26	2.83	11.27	23.33	0.09	15.25	1.94	-12.74	-10.92	-1.03	169.73
26-840	75	274.13	7.13	11.27	44.40	-0.24	19.27	-27.28	-10.84	1.00	-0.08	151.24
26-740	80	22.00	-3.89	-47.68	-30.61	-1.10	-3.00	-13.51	-5.34	1.65	-2.33	83.82
3-502	80	-105.20	-3.26	-77.75	-15.19	-0.63	-36.79	-30.30	-39.95	-19.74	-2.15	130.95
	Average	71.87	4.17	-10.69	16.59	-0.31	-13.01	-8.43	-17.07	-10.86	0.16	75.59

Table 2.3

Element mobility calculations of the hydrothermally altered rocks from Los Azufres geothermal field. Group 3: mafic rocks with a SiO_2-content < 60 wt.%. Sample names designate the well number and depth.

Sample	Alteration	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total	Sp.Grav.
Fresh[1]	0	60.33	0.96	16.66	6.33	0.09	2.06	5.14	3.96	2.25	0.15	1.46	99.39	2.80
52-1480	10	61.23	0.75	16.05	4.80	0.08	2.77	6.53	3.16	2.54	0.14	2.11	100.16	3.00
52-1220	15	60.90	0.86	16.11	5.60	0.07	4.03	5.36	3.01	1.71	0.19	2.33	100.15	2.90
52-1900	15	61.62	0.74	16.84	4.77	0.08	2.40	5.95	4.01	1.73	0.19	1.69	100.01	3.00
52-220	15	60.84	1.23	18.08	6.39	0.07	1.56	4.73	3.46	1.55	0.32	2.44	100.69	2.80
52-1120	20	60.54	0.86	16.02	5.18	0.08	2.82	5.41	3.50	2.25	0.18	3.08	99.92	2.70
52-1680	20	61.54	0.69	15.08	4.79	0.08	2.80	5.51	2.79	1.90	0.15	2.18	97.52	3.00
52-1920	20	61.69	0.74	17.12	4.72	0.08	2.57	5.24	4.40	1.66	0.21	1.78	100.20	2.70
52-1600	30	62.22	0.78	15.79	5.10	0.08	2.94	5.05	3.88	2.52	0.17	1.90	100.43	2.90
52-1780	30	61.68	0.72	16.17	4.88	0.08	3.19	6.14	3.63	1.73	0.19	2.02	100.45	3.00
52-1860	30	61.37	0.72	15.72	5.46	0.09	2.91	6.03	3.77	1.89	0.16	2.11	100.20	3.00
52-420	30	60.53	0.86	16.51	5.35	0.09	2.45	6.58	3.11	1.03	0.18	4.02	100.71	2.30
52-60	30	61.24	1.09	17.37	5.89	0.09	2.03	5.24	3.56	2.38	0.23	1.31	100.43	2.70
26-540	33	60.82	1.17	16.55	6.27	0.12	1.43	4.01	2.84	2.02	0.27	4.74	100.23	2.90
52-1080	35	60.29	0.84	16.12	5.63	0.08	3.05	5.90	2.58	2.81	0.17	2.24	99.70	2.80
52-100	40	61.18	1.10	17.00	6.01	0.08	1.93	5.01	3.27	2.38	0.27	2.08	100.32	2.70
3-98	50	61.31	1.14	16.64	5.52	0.11	1.13	4.59	3.83	2.35	0.23	2.48	99.33	2.80
3-1400	60	62.47	0.69	16.41	4.59	0.09	2.07	5.55	3.50	1.83	0.17	1.64	99.00	2.50
3-1102	70	60.44	0.83	15.62	5.14	0.07	2.45	5.94	3.46	1.68	0.21	2.05	97.89	2.50
26-1080	73	61.48	0.79	14.48	5.00	0.07	3.10	4.81	2.54	2.00	0.19	5.32	99.78	3.10
3-900	75	61.12	0.84	15.53	5.17	0.07	2.18	4.91	1.89	3.61	0.16	2.56	98.04	2.60
26-1000	80	62.96	0.73	13.55	4.42	0.07	2.45	4.24	2.21	2.04	0.16	5.38	98.21	2.60
3-1202	80	60.63	0.81	15.44	5.32	0.09	3.52	5.57	2.54	2.09	0.17	2.22	98.40	2.40

[1] Average of samples AUM 11, LAS 07, AUM 5, A9 2288 and A9 1440 (see text).

Mass per volume (kg/m^3)

Sample	Alteration	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI
Fresh	0	1699.59	27.05	469.41	178.33	2.65	57.92	144.75	111.51	63.44	4.11	41.24
52-1480	10	1834.00	22.34	480.59	143.83	2.31	82.88	195.56	94.80	76.17	4.31	63.20
52-1220	15	1763.51	24.79	466.52	162.18	1.94	116.54	155.05	87.04	49.54	5.41	67.47
52-1900	15	1848.39	22.20	505.10	142.99	2.34	72.11	178.48	120.40	51.74	5.55	50.69
52-220	15	1691.94	34.18	502.85	177.81	2.00	43.35	131.45	96.33	43.24	8.98	67.85
52-1120	20	1635.77	23.29	432.99	140.00	2.27	76.17	146.18	94.60	60.72	4.78	83.22
52-1680	20	1893.13	21.29	463.89	147.29	2.58	86.22	169.44	85.79	58.60	4.71	67.06
52-1920	20	1662.43	19.81	461.38	127.05	2.05	69.25	141.12	118.46	44.76	5.74	47.96
52-1600	30	1796.61	22.61	455.84	147.26	2.43	84.80	145.85	112.09	72.68	4.97	54.86
52-1780	30	1842.30	21.47	483.01	145.78	2.36	95.33	183.38	108.51	51.79	5.73	60.33
52-1860	30	1837.31	21.53	470.55	163.42	2.60	87.01	180.42	112.85	56.50	4.64	63.17
52-420	30	1382.38	19.57	376.99	122.12	2.15	55.95	150.32	71.05	23.64	4.02	91.81
52-60	30	1646.51	29.20	466.92	158.38	2.42	54.55	140.88	95.63	64.01	6.26	35.22
26-540	33	1759.70	33.85	478.88	181.29	3.41	41.49	115.99	82.25	58.30	7.70	137.14
52-1080	35	1693.11	23.67	452.62	158.08	2.16	85.51	165.58	72.54	78.89	4.91	62.91
52-100	40	1646.69	29.69	457.52	161.86	2.23	52.05	134.84	87.96	63.95	7.21	55.98
3-98	50	1728.17	32.11	469.15	155.49	3.02	31.88	129.53	107.99	66.13	6.62	69.91
3-1400	60	1577.32	17.42	414.30	115.85	2.27	52.22	140.25	88.43	46.26	4.27	41.41
3-1102	70	1543.61	21.20	398.98	131.35	1.71	62.57	151.68	88.32	42.86	5.36	52.36
26-1080	73	1910.07	24.67	449.98	155.29	2.30	96.44	149.32	78.82	62.08	5.75	165.29
3-900	75	1620.96	22.17	411.99	137.06	1.86	57.79	130.29	50.26	95.60	4.14	67.89
26-1000	80	1666.89	19.38	358.67	117.10	1.80	64.78	112.38	58.45	54.01	4.10	142.43
3-1202	80	1478.87	19.66	376.67	129.86	2.15	85.91	135.91	61.88	50.9	4.05	54.15

Table 2.3 (Cont.)

Element mobility calculations of the hydrothermally altered rocks from Los Azufres geothermal field. Group 3: mafic rocks with a SiO_2-content < 60 wt.%. Sample names designate the well number and depth.

Mobilised mass (kg/m^3)

Sample	Alteration	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI
Fresh	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
52-1480	10	134.42	-4.70	11.18	-34.50	-0.34	24.96	50.81	-16.71	12.73	0.20	21.96
52-1220	15	63.93	-2.26	-2.88	-16.15	-0.71	58.62	10.30	-24.47	-13.90	1.30	26.22
52-1900	15	148.80	-4.85	35.70	-35.34	-0.31	14.19	33.73	8.90	-11.70	1.44	9.45
52-220	15	-7.64	7.13	33.44	-0.52	-0.65	-14.57	-13.30	-15.18	-20.20	4.87	26.61
52-1120	20	-63.81	-3.75	-36.42	-38.34	-0.38	18.25	1.43	-16.91	-2.73	0.67	41.98
52-1680	20	193.55	-5.76	-5.52	-31.04	-0.06	28.30	24.69	-25.71	-4.84	0.59	25.82
52-1920	20	-37.16	-7.24	-8.03	-51.28	-0.60	11.33	-3.63	6.95	-18.69	1.63	6.72
52-1600	30	97.03	-4.44	-13.56	-31.07	-0.22	26.88	1.10	0.59	9.23	0.85	13.62
52-1780	30	142.72	-5.57	13.60	-32.55	-0.29	37.41	38.63	-3.00	-11.66	1.62	19.09
52-1860	30	137.73	-5.52	1.14	-14.91	-0.04	29.09	35.67	1.34	-6.95	0.53	21.93
52-420	30	-317.21	-7.47	-92.42	-56.21	-0.50	-1.97	5.57	-40.46	-39.81	-0.09	50.57
52-60	30	-53.08	2.15	-2.48	-19.95	-0.23	-3.37	-3.87	-15.87	0.57	2.15	-6.02
26-540	33	60.12	6.80	9.47	2.96	0.77	-16.43	-28.76	-29.25	-5.15	3.58	95.89
52-1080	35	-6.48	-3.37	-16.78	-20.25	-0.49	27.59	20.83	-38.97	15.44	0.80	21.66
52-100	40	-52.89	2.64	-11.89	-16.47	-0.41	-5.87	-9.91	-23.55	0.51	3.10	14.74
3-98	50	28.59	5.06	-0.26	-22.84	0.37	-26.04	-15.22	-3.51	2.69	2.51	28.66
3-1400	60	-122.27	-9.62	-55.11	-62.48	-0.38	-5.70	-4.50	-23.08	-17.18	0.15	0.17
3-1102	70	-155.98	-5.85	-70.42	-46.98	-0.94	4.65	6.93	-23.19	-20.59	1.25	11.11
26-1080	73	210.48	-2.38	-19.43	-23.05	-0.35	38.52	4.57	-32.68	-1.37	1.63	124.05
3-900	75	-78.63	-4.87	-57.42	-41.28	-0.79	-0.14	-14.46	-61.25	32.16	0.02	26.65
26-1000	80	-32.69	-7.67	-110.70	-61.24	-0.85	6.86	-32.37	-53.05	-9.44	-0.01	101.19
3-1202	80	-220.71	-7.39	-92.74	-48.47	-0.50	27.98	-8.84	-49.63	-12.54	-0.06	12.90
	Average	3.13	-3.13	-22.35	-31.91	-0.36	12.75	4.52	-21.76	-5.61	1.31	31.59

and to the strong variability of Ti and Zr contents for the volcanic sequence of Los Azufres.

ELEMENT MOBILITY

Element gain and loss calculations show little compositional changes. SiO_2 is mobile usually added during alteration, thus indicating a general silicification process in the field. Aluminium, on the other hand, appears variably mobile, enriched locally but mainly leached out during alteration, especially from mafic rocks. This is of interest as aluminium is normally assumed to be conserved during alteration, but not very surprising considering the big amount of aluminosilicates present as hydrothermal alteration in the field (Torres-Alvarado, 1996). Ti-content (another element considered to be largely immobile) shows a variable tendency, gaining or losing mass per unit volume but in small amounts for most rocks. Ca and Fe also show an ambiguous behaviour, where gains as well as loss of mass are recorded to different extents. Fe was preferentially removed from the felsic rocks, as well as from the second group of mafic rocks, with a higher SiO_2 content. Na and K are systematically removed from most mafic rocks, while felsic rocks show a mass gain for these alkalis. This agrees with the observation that phases such as sericite and K-feldspar are preferentially present as hydrothermal mineral phases in the upper part of Az-26. Textural trends characteristic of mafic rocks include the partial to complete dissolution of primary aluminosilicate phases and devitrification leading to hydrolysis of primary volcanic glasses, both resulting in net loss of alkali and alkaline earth elements through leaching. In extreme cases there is refractory silicification.

Relative alteration intensities may be qualitatively assessed by a comparison of volatile contents of the samples. The stable assemblage in the alteration mineralogy includes hydrous phases (clays and chlorites) as well as volatile constituents such as sulphur. Total volatile contents of “fresh” volcanic rocks are typically low, generally less than about 0.8 wt.% (Rollinson, 1993). Thus, there should be a correlation between alteration intensity and total volatiles present in the samples. However, this correlation does not necessarily hold for extensively leached rocks, where anhydrous refractory residues (such as quartz) may be concentrated.

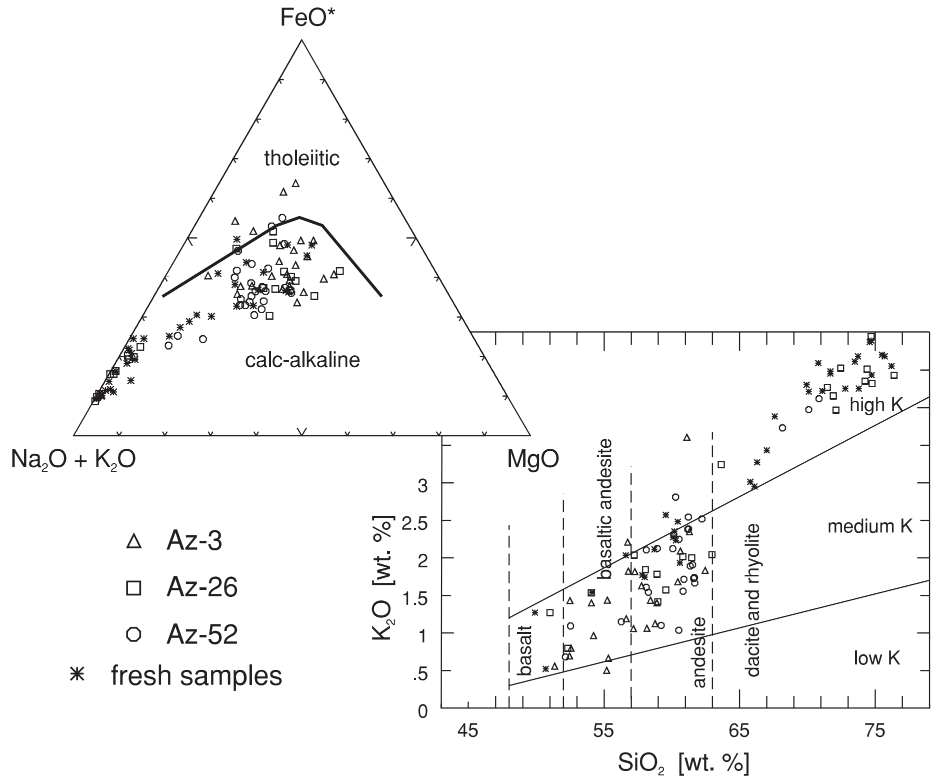

Fig. 2. Classification of volcanic rocks from Los Azufres geothermal field. AFM diagram after Irvine and Baragar (1971); SiO_2-K_2O classification after Le Maitre (1989).

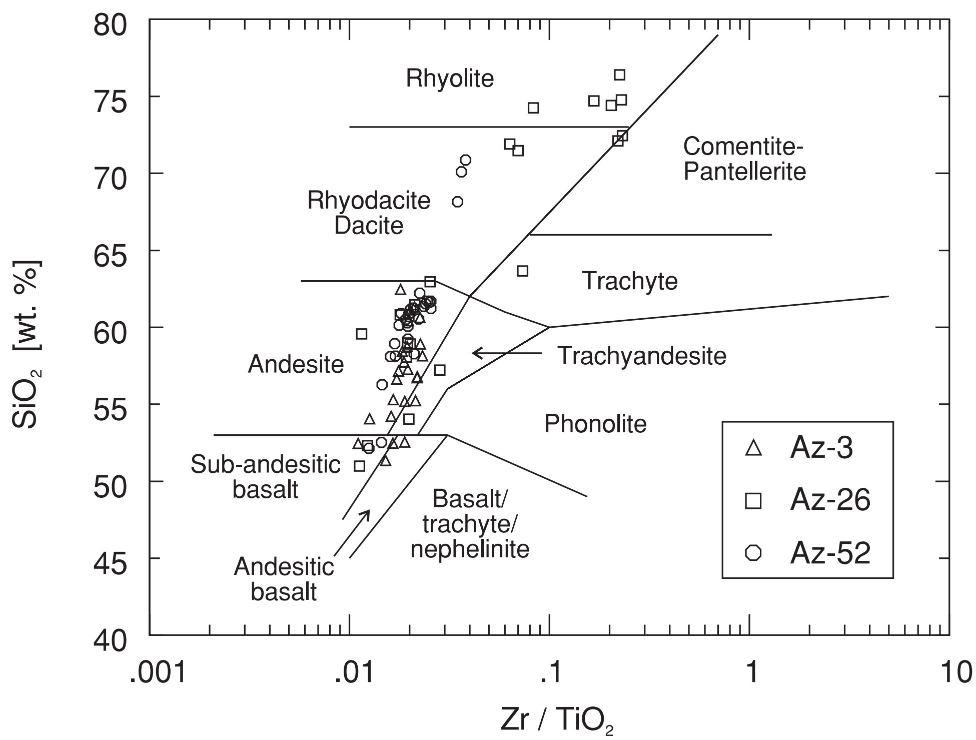

Fig. 3. Classification of volcanic rocks from Los Azufres geothermal field, based on the SiO_2 vs. Zr/TiO_2 diagram of Winchester and Floyd (1977).

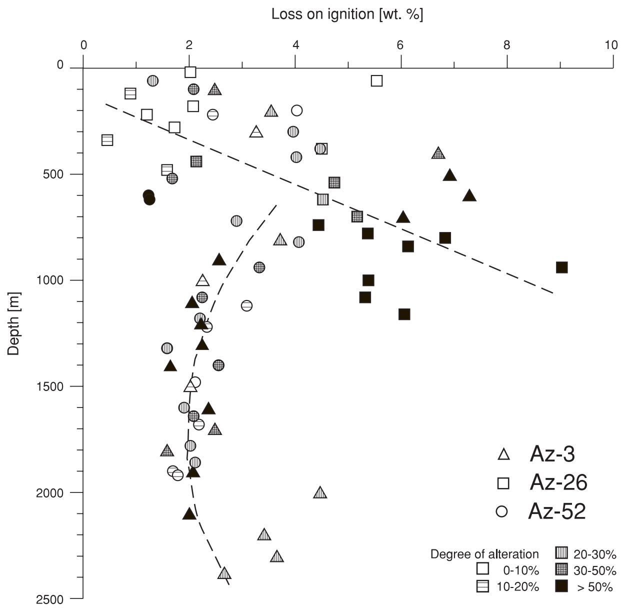

Fig. 4. Loss on ignition vs. depth for samples from wells Az-3, Az-26 and Az-52. Note the shaded patterns showing different alteration degrees in the samples.

Total loss on ignition (LOI) for each sample is plotted against depth in Figure 4. Shaded patterns represent the degree of alteration, quantified as percentages of secondary phases for to the total amount of primary minerals. Two trends can be observed in Figure 4. Samples from Az-26, as well as samples from the first 700 m of Az-3 and Az-52 show a positive correlation between LOI and depth. Below 700 m a nearly constant LOI amount of about 2 wt.% is reached regardless of alteration. The different proportions of hydrothermal minerals can explain this. Well Az-26 contains samples with a relatively high amount of hydrous silicate phases (clay minerals, zeolites and chlorites), all products of hydrothermal alteration at lower temperatures. Wells Az-3 and Az-52, on the other hand, show a higher amount of anhydrous phases such as quartz, epidote and calcite, representative for higher temperatures of mineral formation (Cathelineau *et al.*, 1985; Torres-Alvarado, 1996).

The mass gain and loss (mass/volume) calculations show an important mobility of alkalis in the altered rocks from Los Azufres. This is clearly seen in Figure 5, where total alkalis vs. total amount of earth alkalis for these rocks are plotted. For comparison the "fresh" samples were plotted as well. Figure 5 shows a higher $SiO_2/SiO_2+Na_2O+K_2O$ ratio

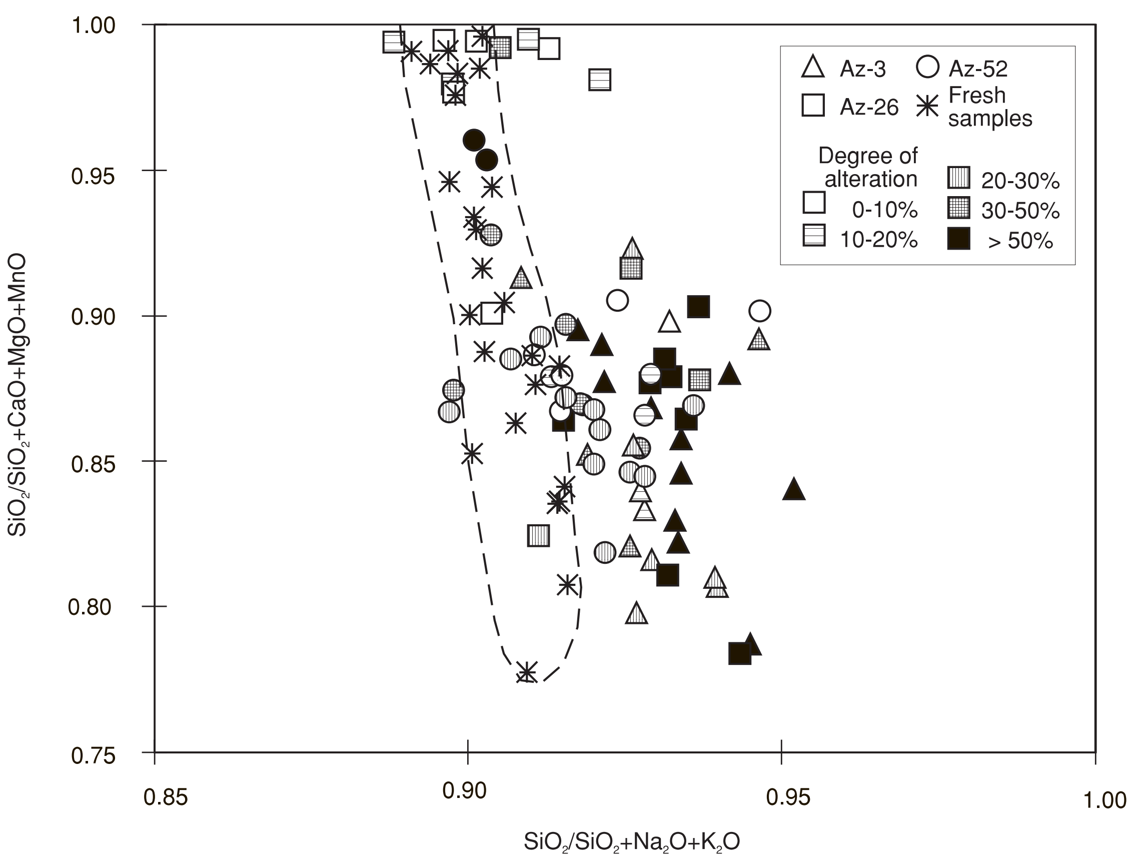

Fig. 5. Alkalis vs. earth alkalis content of altered rocks from Los Azufres geothermal field. The dashed line groups "fresh" rocks for comparison.

(alkalis loss over earth alkalis content) compared to the unaltered samples. A weak relationship between higher alkalis mobilisation and amount of alteration can be observed.

CONCLUSIONS

The rocks from wells Az-3, Az-26 and Az-52 form a calc-alkaline trend from basaltic to rhyolitic composition. Simple calculations of element loss and gain, as well as the comparison of the chemical composition of altered samples to that of "fresh" samples, show relatively low element mobility caused by alteration processes. A general silicification and mobility of alkalis are the most important geochemical changes imposed upon the volcanic rocks by the hydrothermal activity in the Los Azufres geothermal field.

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BIBLIOGRAPHY

AGUILAR Y VARGAS, V. H. and S. P. VERMA, 1987. Composición química (elementos mayores) de los magmas en el Cinturón Volcánico Mexicano. *Geofís. Int., 26*, 195-272.

AUMENTO, F. and L. A. GUTIERREZ NEGRIN, 1980. Geocronología de Los Azufres, Michoacán. Comisión Federal de Electricidad, unpublished report.

CATHELINEAU M., R. OLIVER, A. GARFIAS and D. NIEVA, 1985. Mineralogy and distribution of hydrothermal mineral zones in the Los Azufres (Mexico) geothermal field. *Geothermics*, *14*, 49-57.

CATHELINEAU M., R. OLIVER and D. NIEVA, 1987. Geochemistry of volcanic series of the Los Azufres Geothermal Field. *Geofís. Int., 26*, 273-290.

DE LA CRUZ, V. M., J. S. AGUILAR, D. G. ORTEGA and J. M. SANDOVAL, 1982. Estudio geológico-estructural a detalle del campo geotérmico de Los Azufres, Mich. Comisión Federal de Electricidad, unpublished report.

DOBSON P. F. and G. A. MAHOOD, 1985. Volcanic stratigraphy of the Los Azufres Geothermal Area, Mexico. *J. Volcanol. Geoth. Res., 25*, 273-287.

GARDUÑO MONROY, V. H., 1985. Análisis estructural de la zona norte del campo geotérmico de Los Azufres, Michoacán. Comisión Federal de Electricidad, unpublished report.

GARDUÑO MONROY, V. H., 1988. La caldera de Los Azufres y su relación con el sistema regional E-W. *Geotermia, Rev. Mex. Geoenergía, 4*, 49-61.

GILL J. B., 1981. Orogenic andesites and plate tectonics. Springer-Verlag.

GONZALEZ PARTIDA E., R. M. BARRAGAN REYES and D. NIEVA GOMEZ, 1989. Caracterización mineralógica en 10 pozos del campo geotérmico de Los Azufres, Mich. I: Minerales opacos. *Geotermia, Rev. Mex. Geoenergía, 5*, 347-373.

GRESENS R. L., 1967. Composition-volume relationships of metasomatism. *Chem. Geol., 2*, 47-65.

HUITRON ESQUIVEL R. and A. FRANCO SERRANO, 1986. Carta geológica del campo geotérmico de Los Azufres, Mich., México. *Geotermia, Rev. Mex. Geoenergía, 2*, 211-213.

IGLESIAS, E. R., V. M. ARELLANO, A. GARFIAS, C. MIRANDA and A. ARAGON, 1985. A one-dimensional vertical model of the Los Azufres, Mexico, Geothermal Reservoir in its natural state. *Geoth. Res. Council Trans., 9*, 331-336.

IRVINE, T. N. and W. R. A. BARAGAR, 1971. A guide to the chemical classification of the common volcanic rocks. *Can. J. Earth Sc., 8*, 523-548.

LE MAITRE R. W., 1989. A classification of igneous rocks and glossary terms. Blackwell.

LOPEZ HERNANDEZ, A., 1991. Geología de Los Azufres. *Geotermia, Rev. Mex. Geoenergía, 7*, 265-275.

MORENO OCHOA, J., 1989. Hidrogeoquímica de la región de Los Azufres, Michoacán. Comisión Federal de Electricidad, unpublished report.

PEARCE, J. A., 1983. Role of the sub-continental lithosphere in magma genesis at active continental margins. *In:* C. J. Hawkesworth and M. J. Norry (Eds.) Continental basalts and mantle xenoliths. Shiva, 230-249.

QUIJANO LEON, J. L. and L. C. A. GUTIERREZ NEGRIN, 1995. Present situation of geothermics in Mexico. *Proceedings of the World Geothermal Congress,* Florence, Italy, 245-250.

RAZO MONTIEL, A., R. HUITRON EZQUIVEL and J. N. MOORE, 1989. Geología del campo geotérmico de Los Azufres, Mich. Preliminary Proceedings of the Final Symposium on the Agreement between U.S. Department of Energy and the Comisión Federal de Electricidad de México in the field of Geothermal Energy, 7-15.

ROBLES CAMACHO, J., G. IZQUIERDO MONTALVO and R. OLIVER HERNANDEZ, 1987. Alteración hidrotermal en el Módulo Marítaro, Los Azufres, Michoacán. *Geotermia, Rev. Mex. Geoenergía, 3*, 131-143.

ROLLINSON, H., 1993. Using geochemical data: evaluation, presentation, interpretation. Longman Scientific & Technical, 352 pp.

TORRES-ALVARADO, I. S., 1996. Wasser/Gesteins-Wechselwirkung im geothermischen Feld von Los Azufres, Mexiko: Mineralogische, thermochemische und isotopengeochemische Untersuchungen. *Tübinger Geowissenschaftliche Arbeiten, Reihe E(Band 2)*, 181pp.

VENEGAS, S.S., F.J.J. HERRERA and F. R. MACIEL, 1985. Algunas características de la Faja Volcánica Mexicana y de sus recursos geotérmicos. *Geofís. Int., 24*, 47-81.

VERMA, S. P., 1992. Seawater alteration effects on REE, K, Rb, Cs, Sr, U, Th, Pb and Sr-Nd-Pb isotope systematics of Mid-Ocean Ridge Basalt. *Geochem. J., 26*, 159-177.

WINCHESTER, J. A. and P. A. FLOYD, 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Chem. Geol., 20*, 325-343.

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