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Characterization of Sulfide-Rich Scales in Brine at Reykjanes

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ABSTRACT

The fluid from geothermal wells at Reykjanes, Iceland, is a brine whose salinity is roughly that of seawater and with a temperature of 290 – 320°C. Scaling studies, lasting four to seven weeks, were carried out in 2002 and 2003 as part of an investigation by Sudurnes Regional Heating Company, for a power development project. The general precipitation sequence of scale phases with decreasing pressure was: Wurtsite (ZnS), sphalerite (ZnS), galena (PbS), chalcopyrite ($CuFeS_2$), bornite (Cu_5FeS_4), and amorphous silica. Occasionally other minerals were formed. The amount of scales deposited (i.e. thickness) and, thus, the rate of the scaling depended on the brine composition and the pressure at the precipitation site and the pressure decrease. In surface pipes from well RN-9 at pressure between 20 and 5 bar-g, the scaling rate is between 0.1 and 0.5 mm/30 days (1.2 – 6 mm/year). The silica content is between 13 and 75 wt%, Fe_t – 3 wt%, sulfides 65 and 8 wt%. In pipes from well RN-11 at pressure between 45 and 15 bar-g, the scaling rate is 0.4 and 1.0 mm/30 days (4.9 – 12 mm/year) and at pressure 15 bar and lower it is doubled. The silica content is between 15 and 70 wt%, Fe_t 23 – 6 wt%, sulfides 35 wt%. In pipes from well RN-10, at pressure from 50 to 7 bar-g, the scaling rates varies from 0.2 and 0.9 mm/30 days (2.4 to 11 mm/ year). The silica content is between 5 and 40 wt%, Fe_t 35 – 20 wt%, sulfides 55 and 35 wt%.

1. INTRODUCTION

Mineral scaling can be a serious problem during geothermal energy exploitation and commonly causes problems by restricting fluid flow, preventing valves from closing, clogging surface pipelines and reinjection wells etc. This scaling problem is more pronounced in high than low enthalpy geothermal areas were the liquid is of brine composition. The main scales are amorphous silica, sulphides and iron-magnesium-silicates. For the last decades extensive research been carried out on these areas. Adequate is to name utilized areas like Salton Sea (Skinner et al. 1967, Gallup et al. 1990), Fushime Kyushu Japan (Akaku 1990, Akaku et al. 1991), Broadlands-Okaaki New Zealand (Hedenquist 1990, Reyes et al. 2002) and others areas which are still within reach and yet not utilized like Milos (Karabelas et al. 1989, Andritsos & Karabelas 1991), Nisyros Greek i.e. (Virkir-Orkint 1986) and Assal in Djibouti at the NE cost of East-Africa (Virkir-Orkint 1990). Reykjanes at SW Iceland is one of these high enthalpy areas which have been under development for the last fifty years. Because of increased power, Sudurnes Regional Heating Company stared detailed scaling studies the year 2002. This paper outlines pilot studies made at three wells at Reykjanes where the main purpose was to determine at which pressure and fluid composition these scales precipitated.

2. BACKGROUND

The Reykjanes geothermal area is situated in the extreme SW of Iceland, about 50 km southwest of Reykjavík (Fig. 1). Exploration of the area started in 1956 with the drilling of well 1, a surface exploration phase followed, and an earthquake episode in 1967 gave valuable information. The area was investigated extensively in the years 1968-1970 and there it was concluded that the fluid is not meteoric water but of sea water origin (Björnsson et al. 1972). The early explorations was done for production of common salts and various sea-chemicals for exports (Lindal 1975).

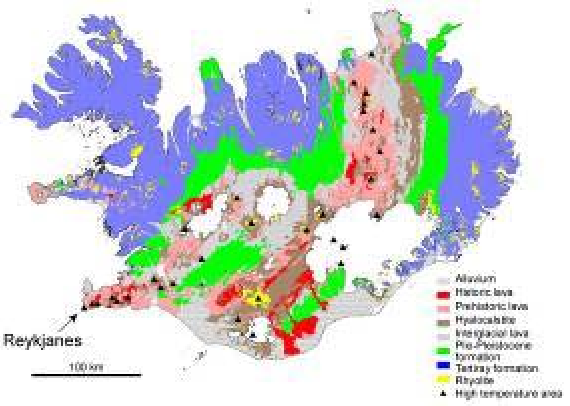

Figure 1: Geological map of Iceland (Haukur Jónhannesson & Kristján Sæmundsson unpublished map 2000), showing the location of the Reykjanes geothermal area.

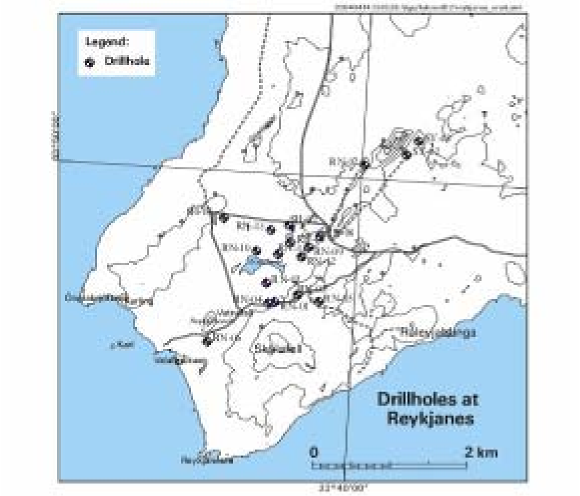

Figure 2: Reykjanes geothermal area, locations of wells.

In 1968 wells 2-8 were drilled, well 9 in 1983 and well 10 in 1999. Since then 6 wells have been completed (Fig. 2) and in the nearest future at least five more wells have yet to be drilled. Wells 8 and 9 have been regarded as extremely successful and have been used for a salt production plant but production from well 8 had was discontinued in 1993 due to a break in a liner and scale deposits.

More detailed surface exploration has taken place in recent years, particularly resistivity measurements. A very important feature of those is the presence of low resistivity on top of high resistivity and the areal extent of such a feature is considered to delineate the subsurface geothermal system. The results of recent resistivity measurements (Karlsdóttir 1997) suggest an areal extent of 10 km^2 for the Reykjanes geothermal system whereas surface manifestations only cover about 1 km^2. The geothermal system is not restrained to the SW and it is quite likely that it extends a considerable distance in that direction below the sea-floor on the Reykjanes Ridge which is a projection of the Mid-Atlantic Ridge. The geothermal system follows a SW-NE fissure and eruption swarm extending into the Reykjanes peninsula which is a subaerial continuation of the Reykjanes Ridge. The eruptions and associated intrusive activity provide a heat source for the geothermal energy and fissure movements retain vertical permeability.

Well logging shows a system with temperature and pressure in accordance with equilibrium boiling to about 900 m depth, but below that a liquid dominated system, reaching temperatures of 280 – 290°C in the NE part but is probably hotter to the SW and at greater depth. Monitoring of utilization combined with computations of mass and heat flow suggest that there is a considerable supply of heat and mass in the system and that it can be expected to be a good producer for a long time (Björnsson 1998).

Ólafsson and Riley (1978) published chemical analyses of water from hot springs and wells 2 and 8, including results for several trace elements. They concluded that the discharge waters are formed mainly by the penetration of local meteoric water into brine-bearing formations followed by evaporation of this brine. Hauksson (1981) reviewed all chemical and isotopic data for springs and boreholes in the area that had been obtained up to that time and concluded that the discharge water was derived from seawater modified by boiling, water-rock interaction and mixing with fresh seawater and meteoric water. He concluded that there was poor permeability at depth in the system and poor flow from deeper strata. Bjarnason (1984) published results for well 9 fluid as well as additional analyses for well 8 and found that the chemical composition of the fluid from the two wells was practically identical. Sveinbjörnsdóttir et al. (1986) and Kristmannsdóttir and Matsubaya (1995) have studied the isotopic (δD, $\delta^{18}O$) composition of the fluids and minerals of the system and related to alteration mineralogy. The former concluded that for a part of the history of the Reykjanes geothermal system its deeper part has been dominated by meteoric water, rather than seawater, circulation, which probably reflects melt-water input or changing sea-level during glaciations. The latter stated that their results are compatible with an origin in a mixture of sea-water and fresh groundwater with about 80% of the present salinity of Svartsengi-Eldvörp brine followed by evaporation, or alternatively the reaction of brines with sheet-silicates formed at a stage of more dilute water, may have changed their isotope ratios. Lonker et al. (1993) summarized studies on mineral-fluid interactions and concluded that at an earlier stage the system was hotter and meteoric, possibly glacial melt-water. They suggest that the system is cooling due to heat source decay, cooler water incursions, or both.

The chemical composition of the fluids from wells 9, 10 and 11 are compared with the composition of sea water reacted with basalts at 300°C and with 35 ‰ salinity as shown in Table 1. The most important deviations from sea water chemistry are magnesium and sulphate depletion and increase of silica, potassium and calcium concentrations all to be expected at high temperatures. The gas concentrations show CO_2 to be the major gas but relatively low H_2S concentration compared to fluids from many other geothermal areas. There is a significant N_2 concentration suggesting that flow from the surface contributes to the fluid. The H_2 and CH_4 concentrations are relatively low; the H_2 concentration reflecting the temperature of the aquifers and the CH_4 concentration suggesting that little or no gas is derived from organic remains in the area.

From the brine in well 8 in Reykjanes down hole scales of iron- magnesium-silicates have formed. Metal sulfides with high contents of precious metals have been precipitated at the wellhead in both producing wells, but are much more prominent in well 9 than in well 8. The sulfide mineral sequence observed is: sphalerite, chalcopyrite, pyrrhotite and galena. The conditions for formation of the iron-magnesium-silicates are not well known, but the sulfides show a clear relation with temperature and pressure and regular sequential precipitation with reduced pressure. The chloride-rich fluids favor the transport of metals which form complexes with chloride, such as the base metals (Zn,

Table 1. **Chemical composition of total fluid (mg/kg) in wells 9, 10, 11, sea water experiment at 300°C (Mottl 1983) and at 35 ‰ salinity (Turekian 1969)**

	9	10	11	Sea-water	Sea-water
No.	2000 -	2003 -	2002 -	Experiment	35 ‰
sample	0513	0679	0274		salinity
°C	290[1]	315[1]	290[1]	300	
pH/°C	5.54/23	5.09/23	5.3/23	5.4-6.0	
SiO_2	667	731	731	895[2]	6.4
Na	10027	9351	9291		10800
K	1443	1412	1348	1250	392
Ca	1633	1503	1624	1224-2178	411
Mg	0.949	1.194	1.39		1290
SO_4	14.90	10.4	14.8		2712
Cl	19615	18528	18034		19800
F	0.18	0.23	0.20		1.3
Al	0.0585	0.0299	0.0583		0.001
Fe	0.82	1.87	1.00	~2	0.003
Zn	0.020	0.140	0.0220		0.005
Pb	<.0006	0	<.00006		
Sr	7.55	8.05	6.86	7.7	8.1
B	8.34	7.32	7.60		4.5
Mn	2.14	5.60	2.92	2.2-7	0.0004
Li	3.71				0.17
Mo	0.015	0.002	0.008		
Cu	<0.002	0	<0.0005		0.0009
Cr	0.0012	0.0002	0.0001		0.0002
Ni	0.0012	0	0.0007		
TDS	33802	32420	31359		
CO_2	1093	1987	1675	169-207	
H_2S	39.36	80	30.13		
NH_3	0.48	0	0		
H_2	0.06	0.29	0.12		
CH_4	0.03	0. 7	0.14		
N_2	2.78	34.19	77.74		

1) mean inflow temperature 2) average of three analyses

Cu, Pb etc.). Boiling causes loss of CO_2 from the liquid phase and consequently increases pH and thus both reducing the solubility of sulfide minerals and causing destabilization of chloride complexes, while H_2S loss favors the precipitation of metals transported by sulfide complexes (Harðardóttir et al. 2001, Harðardóttir 2002).

3. SCALING STUDIES AT WELLS 9, 10, AND 11 AT REYKJANES

The test equipment consists of a manifold with four parallel branches, pipes of 60.3 mm in diameter, each one operated at a different pressure (Figs. 3, 4). The manifold is connected directly to the wellhead. Full wellhead pressure is thus maintained in the manifold and the flow to each branch is throttled by an orifice. The wellhead pressure was 22, 42 and 45 bar-g in wells 9, 11, and 10 respectively. The pressure in each branch is maintained at a different level by adjusting a valve at the exit of each branch. This valve has a back-up orifice plate. The diameter of these orifices is designed to give a specific branch pressure. The distance between locations 4.1 and 4.2 is three times the distance between 2.1 and 2.2 and one branch had five orifices equally spaced along its length to drop the pressure in six stages (location No. 1.1 – 1.6, Fig. 3). Four sets of coupons are close to the inlet just downstream of the flow-controlling orifice (locations 1.1, 2.1, 3.1, 4.1, Fig. 3). The other set of coupons on each branch is near the exit. Coupons of mild steel (50 mm x 15 mm x 2 mm) are held in place on a pipe plug, aligned perpendicularly to the flow direction.

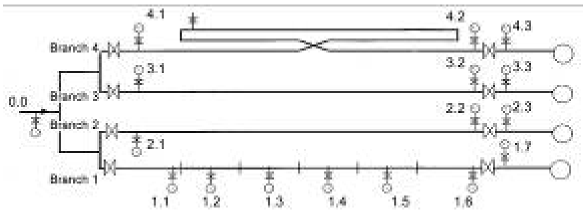

Figure 3: Schematic drawing of the experimental manifold. Individual branches are labeled 1, 2, 3, and 4 and the locations of individual experimental stations are indicated by location numbers (i.e. 0.0, 1.1, 1.2 etc.).

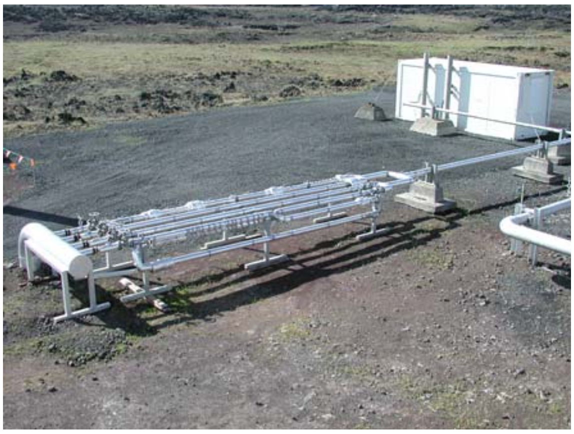

Figure 4: The equipment used in the experiments.

3.1 Procedure

In July 2002 the investigation started at well 9. The coupons were removed from the manifold after 41 days. The investigation was continued in September same year at well 11, and in November 2003 at well 10. The experiments lasted for 41, 30 and 46 days, respectively in the three different wells. The following conditions were met: two coupons were placed at each location, except location 1.1 were 14, 12 , and 10 coupons were placed at wells 9, 11 and 10 respectively, altogether 38, 36 and 34 coupons were involved in each experiment.

The coupons were washed, weighed and their thickness measured, before they were installed. Pressure at each location was measured 3 - 5 times a week. The distance between locations 4.1 and 4.2 is three times the distance between 2.1 and 2.2. The same pressure was obtained at the inlet of the experimental branches and at the wellhead (Fig. 3, location No. 0.0), then different pressures at each branch as shown in Figure **5**. After 4 - 7 weeks the coupons were removed from the manifold, the thickness of the scales was measured and the crystalline scale phases were identified by XRD. Furthermore, chemical “whole rock” analysis was carried out on selected samples.

3.1.1 Results, well 9

The wellhead pressure was 22 bar-g and was fairly constant during the experiments but measured pressure observed in each branch during the study was variable and as an example pressure changes in branch one are shown in Figure **5**. One can see that the pressure is fairly constant at most locations, except 1.1. In branch 2 and 3 pressure increased by a few bar during the experiment but the reverse was observed in branch 4 where the pressure dropped a few bars. The average pressure at each location is considered to be representative, except at location 1.1 where the average for the first 3 weeks was used instead of the 6 weeks, as explained in the discussion. The XRD results are shown in Table 2. Sulfides, such as sphalerite, galena, bornite and chalcopyrite are the most abundant crystalline scale phases on all the coupons. A broad hump, characteristic for amorphous silica, was observed in the XRD patterns at pressures around and below 17 bar-g. Major element analyses of selected scales are shown in Table 3. Scales at locations 2.1, 3.1 and 1.4, 1.5, 1.6 were combined for whole-rock analysis because the amount at each station was to small for individual analysis. This is justified by the very similar pressure, at these stations. The major element composition changes as a function of pressure. At pressures ~10 bar-g and higher SiO_2 is 25 – 15%, Fe_2O_3 5 - 8%, and sulfur and the base metals a between 55 - 65%. At lower pressures (less than about 9 bar-g) SiO_2 is higher than 55%, Fe_2O_3 about 2,5% and sulfur and the base metals around 22%. The amount of scale deposits also increased as a function of decreasing pressure (Fig. 6). The pressure at well RN-09 was always below 20 bar-g and the scaling rate was 0,12 – 0,5 mm/30 days or 1,5 – 6 mm/year. The lowest scaling rate is at the highest pressure around 20 bar-g and at the latter locations at

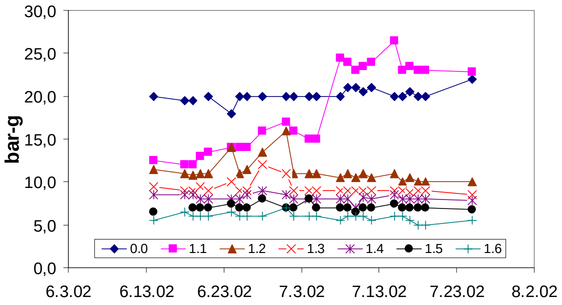

Figure 5: Pressure at 0.0 and in branch 1 as a function of time at locations 1.1 – 1.6 in well 9.

branches two and three were the pressure is 16 – 14 bars (location 2.2 and 2.3 Figs. 3, 6). At locations 2.1 and 3.1 where the pressure is around 17 bar-g the rate is around 3,7 mm/year.

Table 2. XRD results from well 9

Location - No. coupons	Pressure average, bar-g	Results XRD
0.0 (1, 2)	20	sphalerite, galena , chalcopyrite
1.1 (3 – 16)	19	halite, galena, sphalerite, bornite
2.1 (17, 18)	17	galena, sphalerite, bornite, chalcopyrite
3.1 (19, 20)	17	sphalerite, galena, bornite, chalcopyrite
1.2 (21, 22)	11	sphalerite, galena, bornite, opal
1.3 (23, 24)	9	Sphalerite, galena, bornite
4.1 (21, 22)	9	sphalerite, galena, bornite, opal, clay + unidentified
1.4 (27, 28)	8	Sphalerite, galena, bornite
1.5 (29, 30)	7	sphalerite galena, bornite
1.6 (31, 32)	6	sphalerite galena, opal?, + unidentified

Table 3. Concentration of major elements (wt%) in scales on coupons from well 9, Reykjanes

Average Pressure Locations	17 bar-g 2.1+3.1	14 bar-g 1.1	9.5 bar-g 4.1	7 bar-g 1.4 - 1.6	Critical lip pipe
SiO_2	13.49	24.65	26.13	56.23	74.37
Al_2O_3	1.53	3.25	3.52	6.53	4.42
Fe_2O_3	8.17	5.41	4.33	2.64	3.40
MnO	0.458	0.127	0.060	0.035	0.058
MgO	0.20	0.10	0.02	0.11	0.62
CaO	0.57	0.82	0.82	1.27	1.45
Na_2O	0.62	0.97	1.02	2.05	1.23
K_2O	0.27	0.69	0.79	1.42	0.92
TiO_2	0.002	0.006	0.012	0.002	0.102
S	17.70	15.50	15.10	6.50	2.25
Ag	0.182	0.105	0.154	0.167	0.068
Zn	18.73	17.17	16.30	7.86	2.41
Pb	15.29	15.29	10.42	4.474	1.546
Cu	15.32	14.72	13.90	3.443	1.429
Total	92.6	95.5	92.6	92.7	94.3

3.1.2 Results, well 11

The wellhead pressure was 42 bar-g. The manifold experiment at well 11 was discontinued after four weeks, when the well was shut down for repairs but by mistake the coupons stood in the pipes for 4 more weeks and became rusty. To begin with, the pressure readings were fairly constant at high pressure (location 0.0, 1.1, 1.2) then it dropped by about ten to twelve bar at the end of the experiment. At pressures lower than 20 bar-g, the pressure decreased gradually for the first three weeks of the experiment when it leveled off and even increased significantly at stations 1.3 and 1.4. At branches 2, 3, and 4, the pressure was rather unstable but generally the pressure decreases gradually by 15 bars with time. At the end of the experiment it became apparent that the first two coupons at locations 1.1, and the two coupons at locations 2.1 and 3.1 had broken off due to high flow rate. A piece of a broken coupon was blocking the orifice 1.1 thus affecting the pressure at the rest of the locations in branch one. Due to these large pressure changes it was decided to do some research on the orifices as will be discussed later. The XRD results are shown in Table 4. The same trend was observed in the experiment at well 11 as at well 9, i.e. sulphides crystallize at higher pressures and amorphous silica starts to precipitate at pressures below 15 bar-g. Major element analysis was carried out on few of the scales and the results are shown in Table 4. The major element composition changes as a function of pressure (Table 5). At very high pressures (~40 bar-g) SiO_2 is between 15 - 20%, Fe_2O_3 about 23% and sulfur and the base metals a little less than 57%. At lower pressures (less than about 15 bar-g) SiO_2 is between 50 - 70%, Fe_2O_3 12 - 6% and sulfur and base metals between 20 - 8%. Due to rustiness the coupons iron content might not be very accurate. The amount of scale deposits also increased as a function of decreasing pressure. The scale thickness measurements are not very accurate due among other things to rustiness as can be seen in Figure 6. However it can be said that at higher pressures the scale rate is around 0,4 mm/30 days or 5 mm/year and at pressure 15 bar and lower it is double (Fig. 6).

Table 4. XRD results from well 11

Location (No. coupons)	Pressure average, bar-g	Results XRD
1.1 (5, 6)	41	Sphalerite, chalcopyrite
1.1 (9, 10)	41	sphalerite, chalcopyrite, trace of galena
2.2 (33, 34)	37	sphalerite, chalcopyrite
1.4 (37, 38)	9,2	sphalerite, chalcopyrite, galena, opal
1.5 (29, 30)	6,5	sphalerite, galena, chalcopyrite, opal

Table 5. Concentration of major elements (wt%) in scales on coupons from well 11, Reykjanes

Average Pressure Locations	41 bar-g 1.1	40.5 bar-g 1.2	12.6 bar-g 1.3	9.2 bar-g 1.4	5.3 bar-g 1.6
SiO_2	20.54	14.12	43.16	52.28	71.32
Al_2O_3	3.24	1.52	1.13	1.36	1.52
Fe_2O_3	23.41	22.62	11.97	11.25	6.11
MnO	0.314	0.357	0.487	0.289	0.069
MgO	2.83	1.58	0.27	0.24	0.14
CaO	0.99	0.89	0.56	0.58	0.50
Na_2O	1.29	0.58	0.52	0.65	0.90
K_2O	0.72	0.20	0.23	0.29	0.41
TiO_2	0.089	0.043	0.014	0.040	0.025
S	15.3	20.6	13.9	10.2	4.5
Ag	0.230	0.186	0.137	0.119	0.058
Cu	3.85	7.52	5.97	4.98	2.03
Pb	0.55	1.74	3.11	2.67	1.79
Zn	21.9	26.65	17.32	13.39	6.61
Total	95.3	98.62	98.798	98.355	96.02

3.1.3 Results, well 10

This well has the highest inflow temperature in the Reykjanes geothermal area and on average highest in chemical content (Table 1). At location 0.0 the pressure was at first 45 bar-g, but during the first 4 weeks it increased by 7 bar, but decreased gradually over the next three weeks.

This change in pressure is due to a change in the wellhead pressure. At locations 1.1 to 1.6 the plan was to keep the pressure between 30 and 10 bar. This did not work out due to scaling problems in the orifice, gauge etc. The pressure either increased or decreased by a few bar for the first week but over the next two weeks it decreased. The following weeks the pressure increased step by step and at the end of the experiment the pressure was between 43 and 35 bar except at location 1.6 were the pressure was relatively constant around 10 bar. At branches 2, 3, and 4 was a complete different story. The pressure changed drastically after 7 days as shown in Figure 7 and it was obvious that the orifices at locations 2.1, 3.1 and 4.1 were clogged. The orifices were cleaned as well as most of the orifices at other locations. And as can be seen in Figure 7 this clogging problem continued during the experiment and after roughly 3 weeks new orifices were inserted in stead of the old ones. At same time the coupons were also looked on and photographed (Fig. 8). Both sets of the orifices at every locations were examined after the coupon experiment as will be discussed later. XRD-analysis was carried out both on samples from the orifices and the coupons. The sequence of the crystallization was clearly seen: At high pressure wurtzite, a high-temperature form of ZnS was the first mineral to crystallize, followed by sphalerite, chalcopyrite, pyrrhotite and galena. When the pressure was low enough amorphous silica precipitated. Thin skin of dark gray scale, an uncrystallized mass, precipitated before the wurtzite. Major element analysis was carried out on selected samples and the results are shown in Table 6. At pressure above 30 bar silica is 5 wt%, total iron 33 wt%, sulfur and the base metals around 55 wt%, at intermediate pressure, just below 20 bar, the silica concentration is just over 20 wt%, total iron still just over 30 wt% and sulfur and the base metals around 44 wt% and at low pressure, less than 11 bar-g, silica is 37 – 33 wt%, total iron 26 – 22 wt %, sulfur and the base metals 30 – 40 wt%. At this low pressure it is worth noting that at pressure 11 bar-g (location 2.1), silica and total iron are higher than at 8 bars (location 1.6) and the base metals and sulfur are lower at 11 bars than at 8 bar which is expected to be the other way around. But looking carefully through the pressure readings, which were taken 5 times a week, one can see that drops in pressure are much greater at location 2.1 (average pressure 11 bar) than at location 1.6. The pressure difference at location 2.1 bars is ± 13 bars but ± 5 bars at location 1.6. This means the greater the pressure difference the higher silica content is!!! The pressure drop is **the** main cause of silica precipitation. The scale thickness measurements are not very accurate mostly due to enormous scaling (Figures 9 and 10). The scaling rate varies from 0.2 to 0.9 mm/30 days (2.4 to 11 mm/ year). The lowest scaling rate was observed at location 4.2 where the average pressure is 20 bar but that to the distance is three times the other end locations. At locations 0.0, where the pressure was over 40 bar, the scaling rate is found to be 5.6 mm/year.

Table 6. Concentration of major elements (wt%) in scales on coupons from well 10, Reykjanes

Average Pressure Locations	34 bar-g 1.1	19 bar-g 4.1	17 bar-g 3.1	11 bar-g 2.1	8 bar-g 1.6
SiO_2	5.52	22.50	21.87	37.53	33.27
Al_2O_3	0.36	0.42	0.39	0.45	0.54
Fe_2O_3	33.24	32.13	31.26	26.40	22.02
MnO	0.336	0.546	0.576	0.837	0.630
MgO	0.33	0.24	0.24	0.15	0.15
CaO	0.30	0.33	0.30	0.30	0.27
Na_2O	0.57	0.81	0.81	0.78	0.66
K_2O	0.12	0.21	0.12	0.09	0.06
TiO_2	0.009	0.048	0.024	-	-
S	22.79	18.15	18.15	13.59	15.14
Ag	0.113	0.303	0.326	0.239	0.627
Cu	1.38	1.17	1.17	1.28	1.44
Pb	0.67	1.78	2.19	2.33	6.32
Zn	31.38	21.89	22.01	16.08	18.45
Total	97.13	100.53	99.45	100.07	99.58

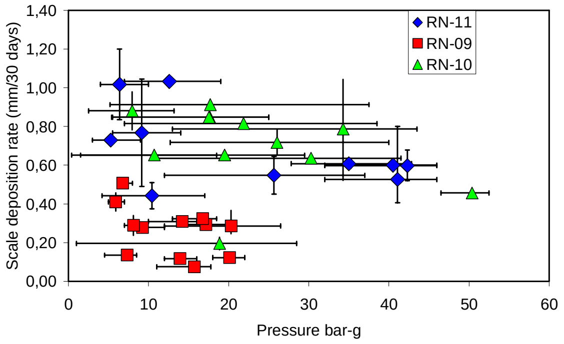

Figure 6. Rate of scaling in experiments in wells, RN-9, RN-10, RN-11.

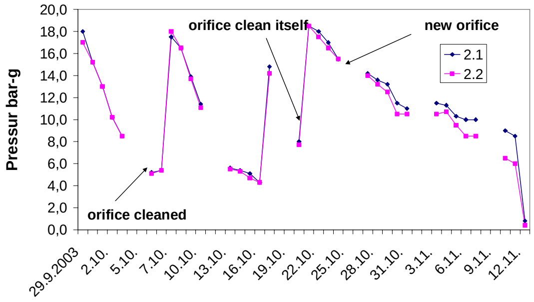

Figure 7: **Pressure changes in branch 2 with time at locations 2.1 and 2.2 in well 10.**

Figure 8: A set of coupons after 3 weeks experiments at location 0.0, RN-10, were pressure was between 46 – 52 bar-g. The golden scale on the coupons holder is chalcopyrite.

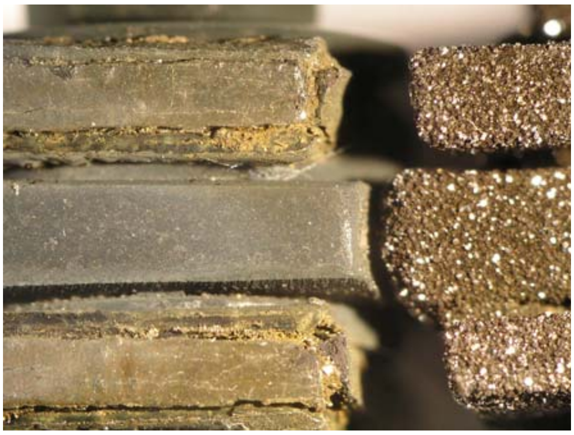

Figure 9: RN-10 coupons from location 0.0 (~ 50 bar-g) and 1.1 (42 - 20 bar-g). To the left there is pyrrhotite at the corroded edge of the coupons, wurtzite to the right.

Figure 10: RN-10 coupons from location 0.0 (~50 bar-g) and 1.6 (~ 8 bar-g). Coupons at 1.6 to the left covered with scale (mostly amorphous silica).

4. DISCUSSION

In the first experiment at well 9 it was noticed that the coupons at locations 1.1, 2.1, 3.1 and 4.1 might be to close to the inlet just downstream of the flow-controlling orifice. The coupons at these location became corroded at the edges which faced the liquid flow. Therefore the locations were moved further away from the orifice. But that did not help in the experiment at well 11 for the coupons broke of after only few days at locations 1.1, 2.1 and 3.1. These broken coupons in one case at least blocked the orifice, which affected the pressure at that location (No. 1.3 well 11). A sudden shift in pressures was observed. The cause could be 1) the pressure gauge pipe became clogged, 2) the orifice was clogged by scaling, 3) foreign piece blocked the orifice, 4) scaling in pipes, 5) change in wellhead pressure and 6) a combination of all these. In the experiments at well 9 the pressure was not very high, always below 20 bar-g and relatively constant in each branch. Only at location 1.1 there was a change in pressure, plus 10 bar-g, which was probably due to clogging of pressure gauge. Small rises or decreases in pressure are probably due to scaling. It was not easy to control the pressure at wells 11 and 10 as was mentioned before. Inspection of the orifice plates revealed a difference in the character of the scales on the upstream and downstream sides of the plates as illustrated in Figures 11 - 13. There is a difference in scaling composition as well as thickness between it is upstream and downstream faces of the orifice. In general, the scales on the upstream side of the orifice were less voluminous and contained more phases typically associated with higher temperatures than did the scales on the downstream side. This difference is a result of the pressure drop over the orifice and therefore not surprising that the scales on individual orifice plates reflect the overall pattern of scale deposits in the manifold experiment.

Examination of the orifice plates under a binocular microscope also revealed different morphologies of scale deposits in the orifice (Figs. 11 and 12). Pillow shaped scales (Fig. 11) were formed at pressure lower than 15 bar-g and the pyramid shaped scales were mostly formed at pressure above 25 bar-g. A drawing of an orifice, showing the flow direction, the locations and composition of the scales is presented in Figure 14. When pressure is very high, in RN-10, a thin skin of uncrystallized mass precipitates, then wurtzite crystallizes. On the other side the pressure drops and sphalerite (usually) wurtzite (sometimes) and galena crystallize. Chalcopyrite is seen in downstream cavities. When pressure is low enough silica precipitates downstream.

In previous studies of scales in wells RN-8 and RN-9 (Hardardóttir et al. 2001, Hardardóttir 2002) it was suggested that some of the scales might have precipitated as an iron-magnesium silicate, similar to scales that have been reported in Salton Sea (Quong 1976, Gallup 1989). The concentration of dissolved constituents is an order of magnitude greater in the Salton Sea brine than in the Reykjanes brine. The scale appears as a brown-black, vitreous solid resembling obsidian. At Salton Sea the typical scale contains total iron (Fe_2O_3) 43 to 37 wt%, silica (SiO_2) 35 to 42 wt%, aluminum (Al_2O_3) 0 to 2.0, calcium (CaO) 0.5 to 1.0, manganese (Mn_2O_3) 0.5 to 1.0 and hydrated water 12.0 to 19.0 wt% (Gallup 1993). These scales does not exhibit an X-ray diffraction pattern and have therefore been termed amorphous and are a non-stoichiometric compound exhibiting iron to silicon mole ratios ranging from about 0.2 to 1.0 as shown in Figure 15 (Gallup 1989). On the same figure are plotted the Fe/Si ratios for samples from the well involved in the experiment (Table 7). In well 9 sulphides at high pressure and amorphous silica at low pressure are well accounted for, but there is some doubt about the iron silicates, which are a substantial part of the scales at some of the higher pressure values. Although there is semblance of these scales from Reykjanes experiments to those from Salton Sea, some of the Fe/Si ratios are between 0 and 1 we believe that only a small amount of these scales form as a iron silicates as is indicated by the Fe/Si ratio. It is likely that Fe and Si form a compound at medium pressure (lower then 20 bar-g), but gradually as pressure is lowered separate oxides are formed. In Reykjanes sulfides are formed at high pressure, at medium pressure the iron silicates start to precipitate followed by amorphous silica at pressure below 16 bar.

Figure 11: Orifice No. 1.4, RN-11 pressure is 14 – 5 bar-g. Black pillows are mostly amorphous silica.

Figure 12: Orifice No. 3.2, RN-11, showing pyramid shaped scale (mostly sphalerite, & galena) where pressure was between 37 – 12 bar-g.

Figure 13: Orifice No. 0.0, RN-10 where pressure was between 49 – 52 bar-g. The scale is wurtzite (ZnS).

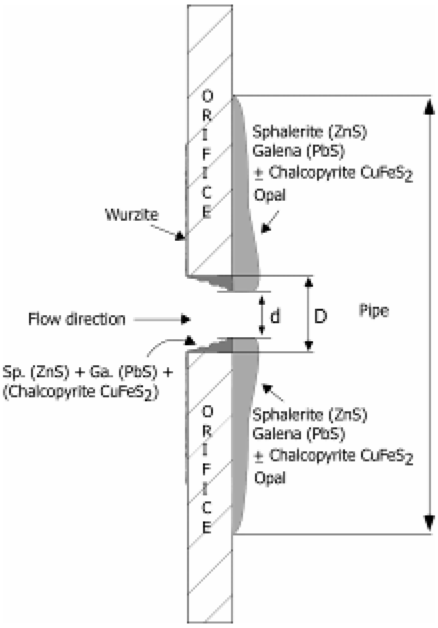

Figure 14: Schematic drawing of an orifice, showing the flow direction, and precipitation of minerals and uncrystallized mass of silica.

Table 7. Fe/Si ratio versus pressure

Well	Location	Pressure (bar-g)	Temp.* °C	Fe/Si
RN-9	2.1+3.1	17	207	0,88
RN9	1.1	14	198	0,32
RN-9	4.1	9,5	182	0,24
RN-9	1.4 - 1.6	7	170	0,07
RN-9	Critical lip pipe	1		0,07
RN-11	1.1	41	253	1,7
RN-11	1.2	40,5	252	2,33
RN-11	1.3	12,6	194	0,41
RN-11	1.4	9,2	181	0,32
RN-11	1.6	5,3	161	0,13
RN-10	1.1	34	242	9
RN-10	4.1	19	212	2,1
RN-10	3.1	17	207	2,1
RN-10	2.1	10,9	184	1
RN-10	1.6	8,2	176	0,98

*saturation temperature at this pressure.

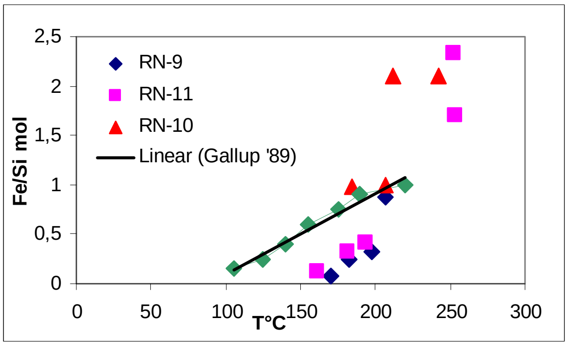

Figure 15: Iron-silicon ratio versus temperature for from scales at Salton Sea and Reykjanes.

5. SUMMARY

The scale formation in the Reykjanes high temperature area is highly dependent on pressure and less on the composition of liquid as evidently shown by coupon experiments carried out in wells RN-9, RN-11 and RN-10. The higher the pressure the lower was the silica content, but in reverse applied to sulfide components. Sulfides like wurtzite, sphalerite, galena, bornite and chalcopyrite crystallize at higher pressure but at pressure below 15 bar amorphous silica starts to precipitate. At RN-9, wellhead pressure 22 bar-g, pressure in branches was maintained in the interval 20 – 6 bar. The scaling rate was 1,5 – 6 mm/year. At RN-11, wellhead pressure 42 bar-g, the pressure was maintained at 42 – 5 bar. The scaling rate was 6 – 11 mm/year. At RN-10, wellhead pressure 52, the pressure in branches was maintained at 52 – 7 bar and the scaling rate was 2.5 – 11 mm/year. In all cases, except one, the lowest scaling rate was observed at the highest pressure and the scaling rate increased with magnitude of pressure drop. The distance between the orifice where the pressure drop and the location of the coupons also affect the scale thickness, i.e. the further away from the orifice the thinner the scales are. At high pressure the dominant scales are sulfides, followed by some iron silicate scale together with iron oxide ot intermediate pressure and then amorphous silica at low pressure.

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