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Successful implementation of Ormat Energy Convertors as Brine Enhancement Units in Flashed Geothermal Fields

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ABSTRACT

Ormat Energy Converters (OECs) as bottoming units provide a comprehensive solution to added power generation from flashed high enthalpy resource fluids. With the proper management of injection temperatures and chemical treatment, additional power may be generated from countless flash systems worldwide. Heat recovery and reinjection of brines below silica or silicate saturation temperatures continues to be a perceptual hurdle for many companies to overcome. Ormat has managed this hurdle with unique thermodynamic design criteria to fit each resource and their scaling conditions; as well as a suite of chemical treatment options and procedures, following years of testing and experience to develop the lowest cost and easiest solution for implementation. High enthalpy flashed brines prone to amorphous silica and aluminous silica scaling will reliably benefit from OEC designs implementing dilution and pH reduction from condensate recombined at the preheater stage. Furthermore, pH modification is recommended where the operational staff, materials and attention can be dedicated to this high precision, yet highly effective solution. Fields without the staff and resources to attend to pH modification may benefit from silica dispersant or inhibitor methods. Deposition of amorphous metal silicates is a common fouling side effect within OECs from lower enthalpy brines, typically with equilibrium concentrations of Al, Mg and Fe to support amorphous silicate formation. We have observed successful inhibition of amorphous metal silicate fouling within surface equipment with the use of organic inhibitors and dispersants. This paper discusses the types of scaling that might be expected within typical bottoming units in a broad host of geothermal resources and the management strategies to support their operation.

1. INTRODUCTION

Bottoming units are a valuable addition to established geothermal powerplants by further utilizing flashed brine and adapting to changing resource conditions in an aging system. The Ormat Energy Converter (OECs) is a binary heat exchanger system, which transfers heat to a secondary, low-boiling point working-fluid to drive a turbine and rotate the generator. In a bottoming unit, the post-flashed brine passes through a shell-and-tube heat-exchanger, heating the organic working fluid inside a closed loop, and is then reinjected (Figure 1). OECs have been successfully operated with brine outlet temperatures as low as 60°C, thus providing a valuable addition to even low pressure flash systems. OECs provide flexibility for changing resource conditions with modular components which may be added over time to better utilize declining resource temperatures and pressures, unlike traditional flash systems. Bottoming units may also be considered a transitional step in the long-term conversion to 100% binary for an aging resource.

A recent example is the Brady powerplant in central Nevada. Originally, a flash plant built in 1992, it was upgraded to include a bottoming unit by Ormat along with other resource improvements in 2002 to gain an 80% upgrade in power generation (Krieger and Sponsler, 2002). Treatment needs were simple, only a neat phosphonic acid to control Mg- rich silicate scaling. As resource temperatures continued to decline, the steam turbine generator (STG) made even less power, thus Ormat replaced the flash plant with another OEC, commissioned in 2018. Currently, the site generates significantly more power with the same resource without the use of the STG. Equally important, chemical treatment is no longer needed and breakdowns are essentially eliminated. Eliminating the flash process eliminated the need for chemical treatment, since all wells are pumped and geofluid is maintained in liquid phase with 100% reinjection.

Ormat operates several traditional flash geothermal plants in the United States, built between the 1980's and 2000's, which have since been upgraded with OEC bottoming units to increased net MW output, enhance efficiency and respond to slowly declining reservoir pressures over decades of exploitation. Each OEC contributes between 20-33% of total facility electrical production (Table 1). The impact of this modification includes prolonged lifespan of the wellfields beyond the design efficiency of the traditional flash plant. In many cases, complete binary OEC repowers are planned for the future to fulfill a renewal of the power purchase agreements.

Table 1: Examples of Ormat operated facilities' power generation increase with bottoming units compared to power generated by flash plant only.

Facility Location	Date Flash plant commissioned	Flash Plant [MW(net)]	Date OEC commissioned	OEC Inlet temperature [°C]	OEC Outlet temperature [°C]	OEC [MW(net)]	OEC power generation Increase [%]
Southern California	1985	31.5	2006	100	71	8.0	20.3
Southern California	1986	23.7	2007	102	74	7.3	23.5
Nevada	1992	18.9	2002	111	84	4.4	18.9
Nevada	1988	8.7	2007	136	97	4.2	32.6
Hawaii	1993	26.3	2011	205	95	11.3	30.1

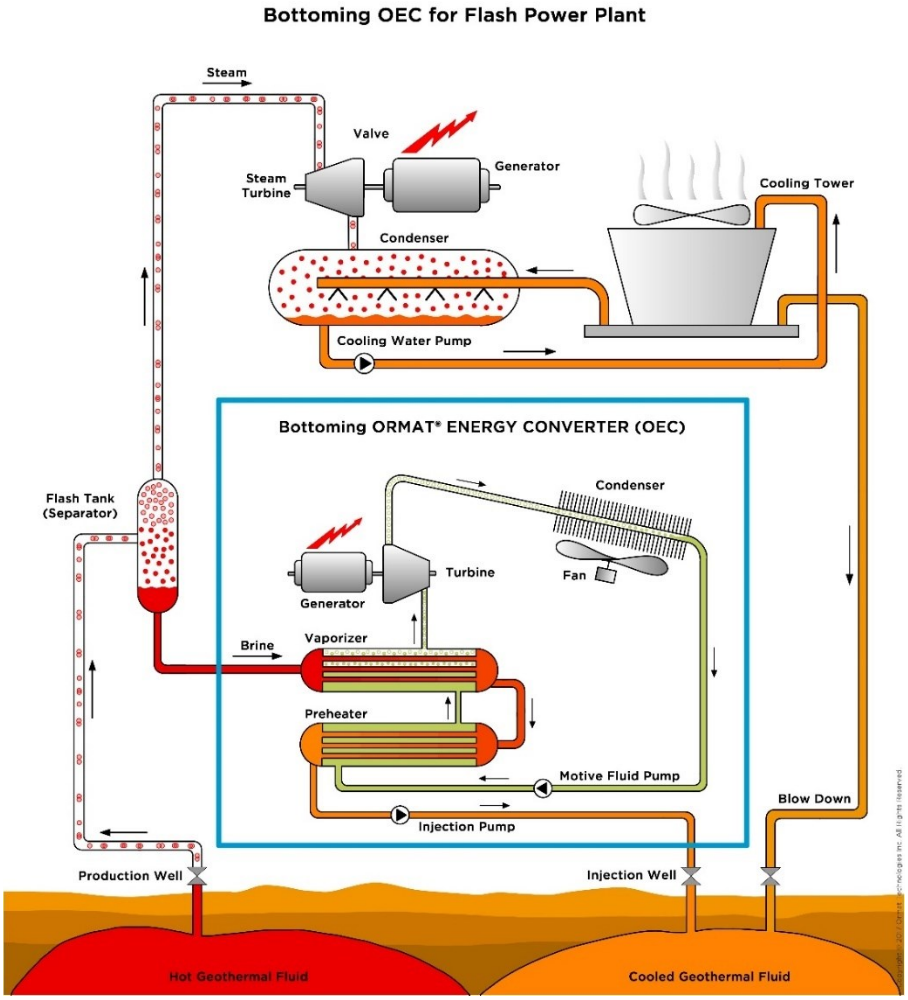


Figure 1: Schematic illustrating combined cycle geothermal powerplant with stage 1 flash separation and steam turbine, followed by a stage 2 brine cycle comprised of vaporizer and preheater heat exchanger as part of the Ormat Energy Converter (OEC).

2. SCALING POTENTIAL

2.1 SCALE CHARACTERIZATION IN BOTTOMING UNITS

A common issue with bottoming units includes enhanced saturation of scale-forming minerals as flashed brines are cooled to outlet temperatures of 70-100°C. However, thanks to several commercial chemical treatment options and customized thermodynamic designs, the impact of this supersaturation on MW generation may be successfully mitigated.

Scale-forming minerals collected from Ormat's fleet of flashed brine plants are analyzed and catalogued below (Table 2). The primarily scales observed within these bottoming units can be generally categorized as either [1] amorphous metal silicates, or [2] amorphous Al-rich or Fe-rich silica. The first category, described here as amorphous metal-silicates, may be characterized as Fe- or Mg-rich amorphous phyllosilicate mineraloids, with stoichiometric molar ratios resembling that of clay minerals with Al-substitution of the tetrahedral layer. (Fe+Mg)/(Al+Si) ratios, represented here as the ratio of possible octahedral layer-forming cations to tetrahedral layer-forming cations, average 0.5 or higher, with decreasing Al/SiO2 ratios as (Fe+Mg)/(Al+Si) ratios increase (Figure 2). These scales often appear as having a vitreous morphology and amorphous X-ray pattern nearest to the depositing surface, overlain by granules of clay minerals occurring near the surface, possibly from aging and recrystallization of the amorphous substrate over time (Figure 3 and 4). Surface crystals often display a characteristic clay morphology with definitive XRD patterns, while they retain nearly identical chemical composition to the bulk amorphous scale.

The second category of scales may be categorized as Al- or Fe-rich silicas with (Fe+Mg)/(Al+SiO2) ratios <0.1 and Al/Si ratios ranging from 0.03 to 0.20. These scales exhibit amorphous XRD spectra with broad peaks over the 25^{o} 2θ range consistent with Opal-A. Morphology by SEM may appear as colloidal aggregates as well as vitreous, amorphous material (Figure 5). Much like the above metal silicate scales, varying morphologies identified under SEM exhibit similar chemical compositions within the same section. Previous authors have described similar Al or Si rich silica scales, occurring in places such as the Salton Sea and Indonesia, as polymorphs of histringerite or halloysite, containing Al/Si ratios of averaging 0.1-0.2 (Gallup, 1997; Gallup, 1998; Manceau et al, 1995).

Lower temperature and lower salinity geothermal systems such as Bradys and Ormesa are represented as magnesium-rich amorphous silicates with molar metal-Al-Si ratios congruent with smectites or other phyllosilicate minerals (Table 2). Higher salinity systems such as Heber, deposit more Fe-rich metal silicates and Fe-silicas (Figure 2), reminiscent of scales reported at the Salton Sea (Gallup, 1989; Manceau et al, 1995). For the above examples, early flash vessel scales exhibit higher concentrations of calcite and amorphous metal silicates, while bottoming-unit scales become increasingly depleted in octahedral layer-forming cations. Despite this trend, crystalline clay minerals such as montmorillonite, vermiculite and saponite appear to form over time at the expense of originally deposited amorphous polymorphs within the cooling conditions of the heat exchangers.

Higher temperature and higher salinity Puna scales form aluminous-rich amorphous silicas throughout the process, heavily seeded early on by iron and heavy metal sulfides near the initial point of separation. Later within the bottoming units, as silica saturation increases, the concentration of Al/Si decreases as colloidal silica agglomerates to Al-rich seeding particles. Much like the above lower-temperatures scales, crystalline polymorphs appear along the surface of vitreous scales and grow into more organized scale networks, suggesting an aging or maturing process over time.

2.2 Factors attributing to scale formation

An important commonality among scales forming within flashed brine bottoming units is that they each undergo flashing prior to heat exchange and cooling within the OECs. It is likely that many important seeding minerals become supersaturated during this flash process due to rapid increases in pH, such as calcite, other pseudo-phylosilicates or heavy metals sulfides. Figure 6 illustrates increasing saturation indices for several scale-forming minerals identified within the Heber process following the pH change accompanying the initial high pressure flash. Following this stage, the brine passes through the OECs where cooling increases the degree of supersaturation, namely for amorphous Al- or Fe-silicas. Geothermal brines appear to be undersaturated or at saturation with respect to both Al- and Fe-amorphous silicas upon the inlet to the OECs for most wellfields, yet exit the process at Q/K values of ~2.0 or more (Table 3). The reaction process of hydroxyl aluminum and iron complexing with silicic-acid oligomers appears to dominate at lower temperatures resulting in increased tetrahedral substitution of Al or Fe with silica. Furthermore, polymerization of Al and Fe rich silicas are also enhanced at pH increasing from 7-9 (Gallup, 1997; 1998), such as induced through the flash process. Based on the above observations, aluminum, iron and magnesium may be critical limiting reagents in the formation of scale seeding mineraloids throughout the brine cooling process. In addition, pH increases due to flashing also affect the type and rate of scale formation, suggesting that this variable may be stabilized to prevent OEC fouling.

3. SCALE MITIGATION AND PREVENTION

Scale formation in many geothermal systems is an unfortunate, but inevitable, operation and maintenance byproduct. Improvements should be measured against reduced downtime, extending lifetime between cleanings or minimizing loss of thermal exchange capacity, rather than total elimination of scale. While several chemical treatments and design features are recommended here, successful mitigation of scale products must be approached from multiple sides, rather than relying on a "silver bullet" treatment.

3.1 Chemical Treatment

Chemical treatment of brine with additives can be a highly effective solution for mitigating scale, whether by pH modification or organic inhibitors. pH modification is a well-tested method for inhibition of scale polymerization and precipitation. Amorphous silica scale and Fe-silica scale is well inhibited below 4.5 to 6 pH, while aluminous-silica scale typically requires <5 pH for similarly effective treatment. Strong acids such as sulfuric acid, sulfurous acid and hydrochloric acid, work well to achieve these lower pH values at economic rates and dosing, while complexing acids such as glycolic acid, formic acid, and other carboxylic-forming acids work to both reduce pH and sequester metal-hydroxide complexes from reacting with silica.

Amorphous silica and aluminous silica are successfully inhibited within various Ormat facilities by pH modification using 98% sulfuric acid, a specialized acid-dosing skid and proper administration of inexpensive filming amines to prevent corrosion on the surface equipment at low pH. Because excursions above or below the target brine pH can lead to unwanted scaling or corrosion, proper application of this technique requires a customized design to support the facility and resource chemistry, with acid dosing rate control subject to online pH value, complete with automation, redundancy and the proper materials and controls. Furthermore, pH modification requires dedicated, safety conscience, operators to monitor and facilitate its functionality.

Organic inhibitors and dispersants are another proven mechanism for scale mitigation within Ormat bottoming units. Based on the evaluation of the above mineral deposits (Table 2), mitigation of seed-forming precipitates and colloids early in the process can effectively reduce fouling later within the OECs, piping or injection wells. Sequestering agents (crystal growth inhibitors) with functional groups that form relatively strong complexes with aluminum or other cations can prevent the formation and precipitation of amorphous metal silicates as well as aluminous silica in several cases. Such treatments are particularly impactful if dosed before the primary flash point, yet can be administered throughout the process for extended utility. The added use of dispersants improves the functionality of some chemical treatment programs by prolonging polymerization and deposition of suspended solids. Amorphous metal silicate scales at Ormat facilities have been successfully inhibited throughout decades of operations using commercially available copolymer blends, utilizing the benefits of both inhibition and dispersant properties. As with any chemical treatment program, proper administration of organic inhibitors requires a customized treatment program from an experienced vendor. For instance, the chemistry of the brine and precipitate minerals can dictate which complexing agent(s) may be used in a specific inhibitor blend. We strongly recommend commercial vendors with geothermal-specific experience and applications, a track-record of treatment success, and the ability to customize and model the application to the specific resource chemistry or conditions.

3.2 Design Factors

Ormat custom designs each power plant for each project to specifically address the unique needs of the customer, resource capacity and longevity, air or water cooling/condensing options, location and elevation, as well as resource chemistry. The goal of each design is to maximize power generation for the available resource while minimizing operation and maintenance (O&M) costs.

During the design process, scaling and corrosion potential is evaluated for each resource by chemical and material engineers to estimate the type, and rate of fouling and corrosion to be expected. The evaluations are based on geochemical models, geologic or resource analogues, plant process flow, heat and mass transfer as well as metallurgic compatibility. Several factors within the OEC design process may be manipulated to minimize rates of scaling while optimizing thermodynamic efficiency, such as flash pressure, outlet temperatures, velocity within the heat-exchanges, number of passes or rate of cooling, pipeline design, control valve design and separator design. As an example, heat exchanger fluid velocities are designed to a balanced value between being high enough to minimize fouling accumulation, depending on potential scale reaction rate, but not so high to cause surface erosion.

An important component of OEC binary technology in the reduction of scaling potential is the ability to reintroduce condensed stream into either the preheater stage or injection lines to both dilute the mineral-saturated brine as well as lower pH. Increased diluted brine for reinjection not only further supports pressure within the reservoir, but helps maintain the longevity of the injection wells. While several types of scaling benefit from a reduction in overall pH, such as amorphous metal silicate and aluminous silica as highlighted in this paper, other scales such as Sb- or As-sulfides exhibit increased saturation at lower pH (Brown, 2011). As a result, the design process evaluates the type and risk of scaling for a given resource, as well as the ease or cost of maintenance, against the thermodynamic benefit of reintroducing condensate into the heat exchangers.

Design metallurgy represents a critical component, not only for construction costs, but O&M sustainability. The resource chemistry, fluid mechanics, heat and mass transfer are criteria for material selection. Acidic resource chemistry, higher NCGs, higher salinity, potential for corrosive scales or introduction of a pH-modification inhibition system typically requires a unique selection of higher-grade materials and manufacturing techniques for the plant equipment. The increased cost of metallurgy must outlast the maintenance or replacement costs within the design, however, and thus are evaluated as part of the anticipated lifetime of the plant. Some scale maintenance programs may simply include annual or biannual hydroblast cleaning by which robust enough materials should be selected to withstand frequent turbulent cleanings. Online chemical cleanings, such as with HF, to remove scale are often successful and cost efficient; plants for these operators are designed with this chemical interaction in mind.

Our plant design supports best known methods of operation and maintenance from our operating plants experience. Within the Ormat-operated bottoming units, we attempt to minimize rapid upsets or pressure changes to the process, which can cause water hammering, thermal shock to the pipelines, or localized flashing at pressure drops. For instance, we recommend gradual start-ups and shut- downs with the use of variable frequency drives (VFDs) to buffer changes to the injection pressure on the outlet of the OECs. The use of basket strainers, Y-strainers and sometimes sand strainers are implemented upstream of the OEC gathering system to prevent packing off of liberated scale or mineral seeding that can cause smaller tube blockage. Good corrosion control is also critical by preventing excess iron in solution that may induce scaling and by preventing under-deposit corrosion, which can lead to pitting and leaks. Lastly, we recommend effective cleanings of the OECs using high pressure hydroblasting at minimum 20,000psi and heat exchangers layout design enables the operation. Bare metal cleanings not only greatly improve heat transfer, but extend lifetime between cleanings by reducing scaled surface area for future deposition. Reputable and experienced hydroblasting vendors will recommend specialized cleaning nozzles and techniques, which can manage even hard, vitreous scales.

4. CONCLUSION

OECs provide an important solution to prolong the economic viability of a geothermal resource, particularly as bottoming units for existing powerplants not ready to make the full conversion to binary technology. Scaling within the OEC bottoming units is a perceptual hurdle for many operators, however this can be managed with an understanding of the types of scale, appropriate process designs and mitigation strategies. Low temperature systems have a tendency to produce amorphous metal silicate scales within the bottoming unit heat exchangers, stoichiometrically resembling phyllosilicate clays. High temperature systems have a greater tendency to produce aluminous silica or amorphous colloidal silica. Both forms of scale are readily inhibited by either pH modification or sequestering agents focused on disturbing Fe, Mg or Al complexation. Ormat has successfully maintained continued generation with maximum availability for over a decade with the use of the above methods.

Table 2: Characterization of metal-silicate and Al/Fe-silica scales within bottoming units by XRD and EDS, XRF and ICP (molar concentrations), spanning 2009-2019.

			Average molar ratio				
Field	**XRD analysis**	**Morphology**	**Al/Si**	**Mg/Si**	**Fe/Si**	**Mg/Fe**	**(Mg+Fe) /(Si+Al)**
Heber Flash Vessel	Smectite + Calcite peaks	Vitreous/amorphous	0.04	0.20	0.53	0.37	0.69
Heber Al/Si-rich Bottoming Unit	Primarily broad amorphous content (centering at 25deg 2alpha) + Saponite peaks	Physically hard/vitreous to sandy. Vitreous habit with small grains forming on surface + silica colloids observed	0.17	0.02	0.06	0.42	0.07
Heber Fe-rich silicates Bottoming Unit	Vermiculite + magnesioferrite + amorphous content	Vitreous, hard flakey scale; elsewhere porous tubular habit along with flakey vitreous scale underneath	0.12	0.09	0.40	0.27	0.44
Heber Soft scale Bottoming Unit	Saponite + amorphous content	Distinct smectite/mica appearance forming on vitreous surface	0.13	0.04	0.24	0.19	0.25
Ormesa Flash vessel	Calcite + Smectite + amorphous silica (Opal-A)	CaCO3 appears vitreous + magnesium silicate (smectite) appear as knobby microcrystalline materials	0.04	0.60	0.04	15.07	0.62
Ormesa Bottoming Unit	Primarily Smectite + Goethite + Illite	Hard Mg silicate scale w/ Fe-oxides appear vitreous, predominates in GBU vaporizer; softer smectite generally increases in the later/cooler appears w/ classic habit, webby, network of porous matrix	0.05	0.51	0.07	8.05	0.55
Desert Peak OEC	Saponite plus amorphous material	Small grainy crystals forming over vitreous surface	0.05	0.61	0.13	7.41	0.70
Steamboat Bottoming Unit	Aragonite + Vermiculite	Vermiculite appears crystalline and occurs near flash depth	0.04	0.73	0.02	40.84	0.73
Puna Brine Header	Amorphous (possibly Fe-Mn oxy/hydroxides) + Amorphous Silica (Opal A) + Sphalerite + Pyrrhotite + Geothite	Microcrystalline morphology, small colloids agglomerates forming small sub-rounded crystals	0.16	0.01	0.18	0.05	0.17
Puna Vaporizers	Opal A +Opal CT + Fe-rich Amorph silica + smectite - Vermiculite detected	Low crystalline (amorphous) material; some type of magnesium silicate	0.03	0.00	0.08	0.08	0.08
Puna Preheaters	Amorphous + Christobolite + geothite	Low crystalline (amorphous) material; silicate of Ca+Mg	0.07	0.00	0.05	0.01	0.04
Puna Plant outlet	Fe-Al-rich silica + microcrystalline, clays	Microcrystalline morphology, small colloids agglomerates forming small sub-rounded crystals	0.08	0.02	1.18	0.02	1.11

Table 3: Typical Brine properties of Bottoming Unit fluids. Thermodynamic saturation indices (Q/K) for Amorphous silica (Fournier, 1981), Aluminous Silica and Iron Silica (Gallup, 1998) at each stage of the process illustrated as well.

Field	Temp [°C]	pH [STP]	EC [uS/cm]	Mg [mg/kg]	Al [mg/kg]	Fe [mg/kg]	SiO2 [mg/kg]	Ca [mg/kg]	K [mg/kg]	Na [mg/kg]	Q/K Amorph-Si	Q/K Al-Si	Q/K Fe-Si
Heber - downhole	160	6.0	23,700	2.2	0.04	0.1 to 0.04	230	850	318	3900	0.3	0.4	0.6
Heber - OECinlet	110	8.1	26,000	2.6	<0.045	0.2	220	903	365	4333	0.5	0.8	0.9
Heber - OECoutlet	70										0.9	1.8	1.7
Ormesa - downhole	163	6.2	11,000	0.58 - 1.13	0.09	<0.050	209	38	160	2380	0.3	0.4	0.5
Omesa - OECinlet	100	9.0	13,000	1.1	<0.045	<0.050	235	43	183	2640	0.6	1.0	1.1
Ormesa - OEC outlet	70										1.0	1.9	1.8
Desert Peak - downhole	165	6.0	7,000	0.3	0.07	0.050	173	94	149	1964	0.2	0.3	0.4
Desert Peak - OECinlet	110	8.0	9,800	0.4	0.1	0.050	240	131	208	2731	0.6	0.8	1.0
Desert Oeak - OEC outlet	70										1.0	1.9	1.9
SBH- downhole	165	6.3	3,300	0.1	0.24	0.005	337	13	63	604	0.5	0.6	0.8
SBH - OECinlet	129	8.3	3,800	0.1	0.274	0.006	372	15	69	666	0.7	1.0	1.2
SBH - OEC outlet	70										1.5	3.0	2.9
Puna - WH	295	5.4	25,000	0.1	0.152	<0.05	632	147	804	4179	0.4	0.7	0.8
Puna - OEC inlet	206	6.0	28,000	0.2	0.13	0.1	845	205	1100	5650	0.9	1.1	1.5
Puna - OEC outlet	90										2.6	4.2	4.5

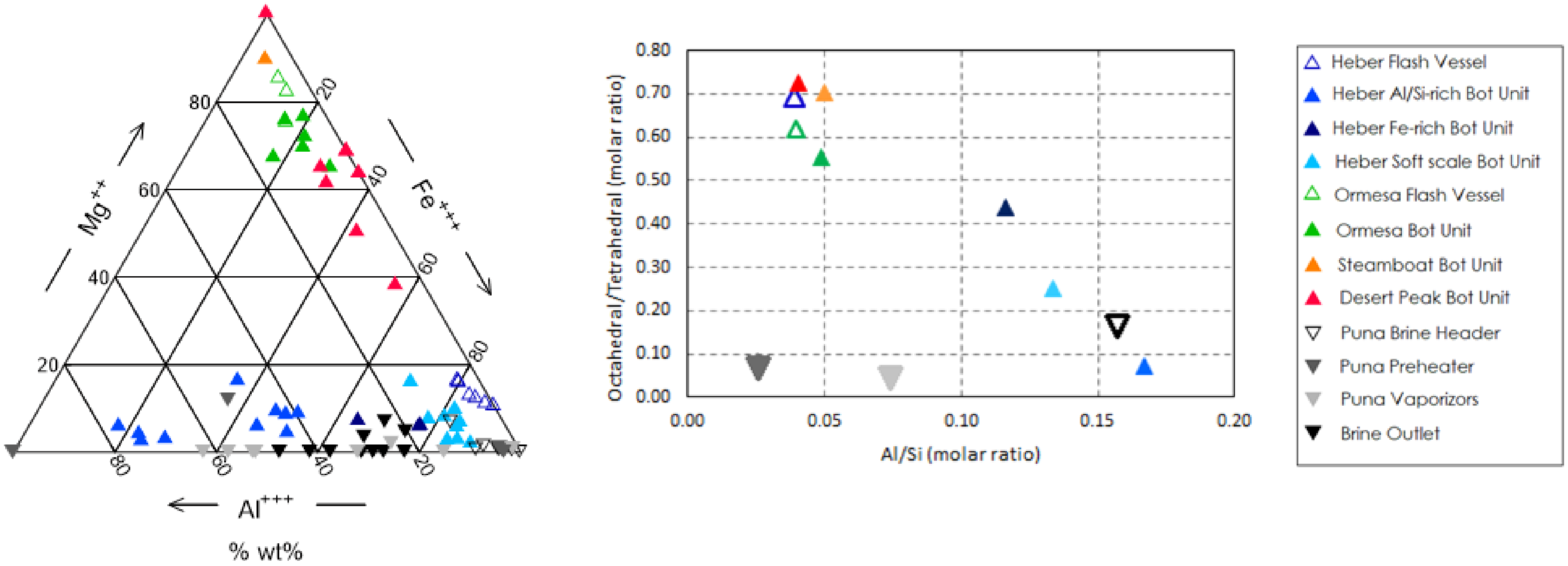


Figure 2: (Left) Ternary plot Mg, Fe, Al concentrations (wt%) within typical bottoming unit scales from Table 2.; (Right) plot (Mg+Fe)/(Si+Al) vs Al/Si molar ratios within typical bottoming unit scales.

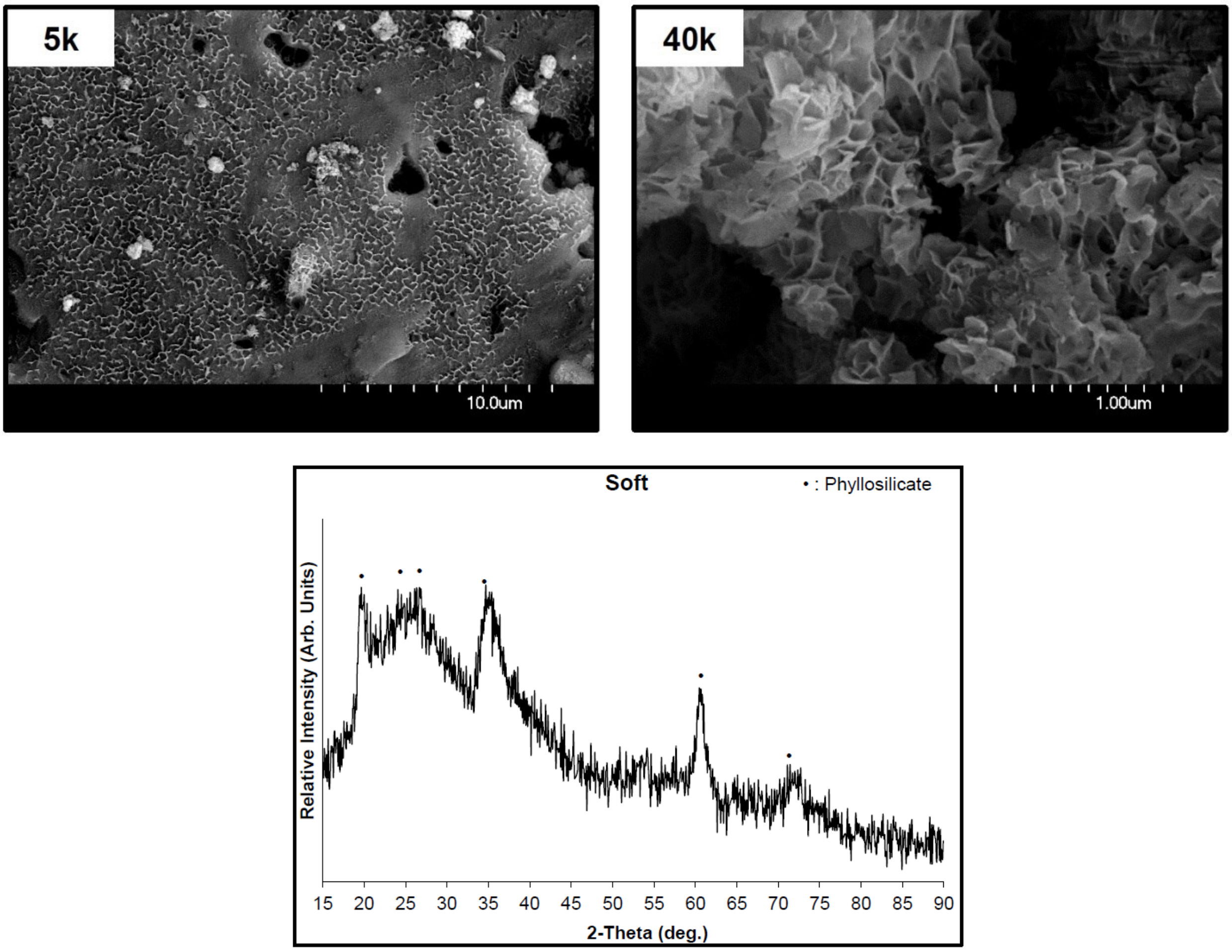
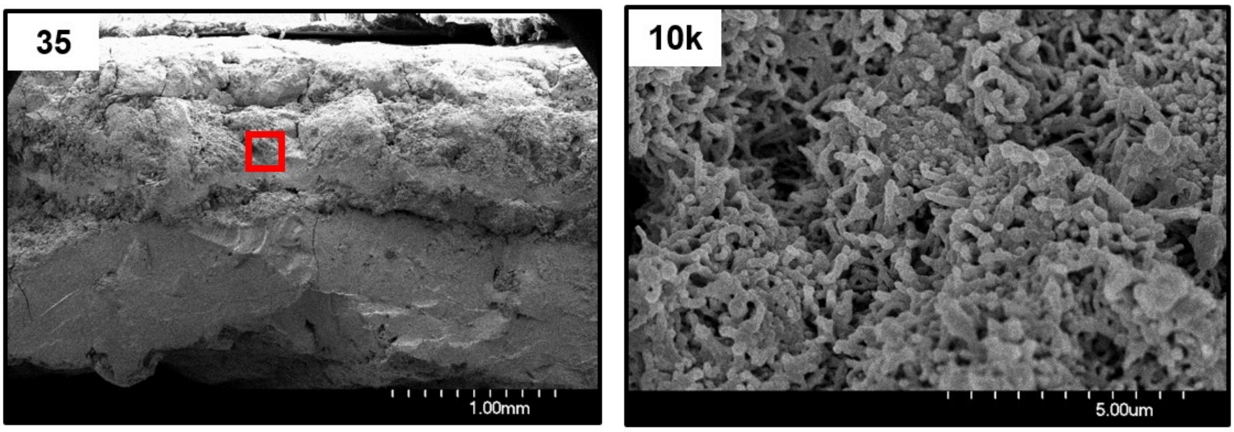


Figure 3: (Upper) SEM image (at 5K and 40K magnification) of crystalline micaceous minerals forming on top vitreous subsurface. Scale collected from Heber bottoming unit. (Lower) XRD diffractogram from sample exhibits broad pattern indicating amorphous content overlain by crystalline saponite.



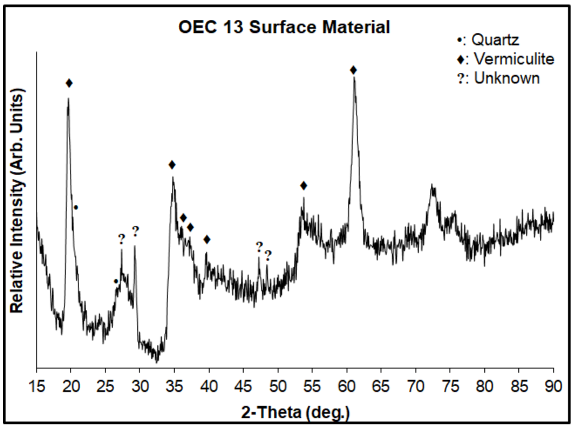


Figure 4: (Upper) SEM image (at 250x and 10k magnification) of sample from Heber bottoming unit pulled during plant excursion. Material exhibits colloidal silica spheres near surface. (Lower) XRD diffractogram from crushed and sieved scale sample (< 300um) suggesting majority of scale material is amorphous silica content.

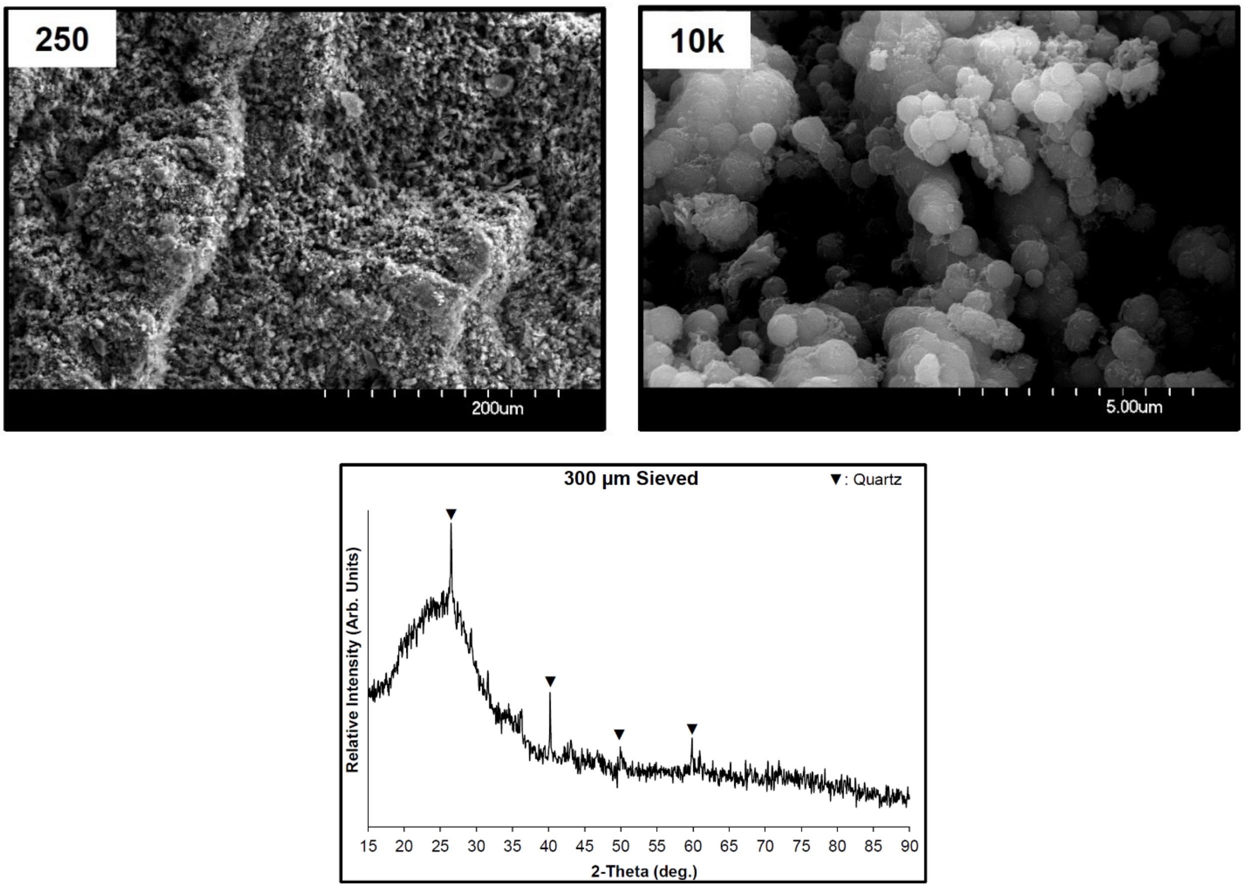


Figure 5: Plot of saturation indices (Q/K) for common scale-forming minerals such as amorphous silica, calcites and crystalline polymorphs (smectites) of scales observed in Heber, occurring during the HP flash process with exsolution of CO2 and decrease in temperature from 165°C to 127°C.

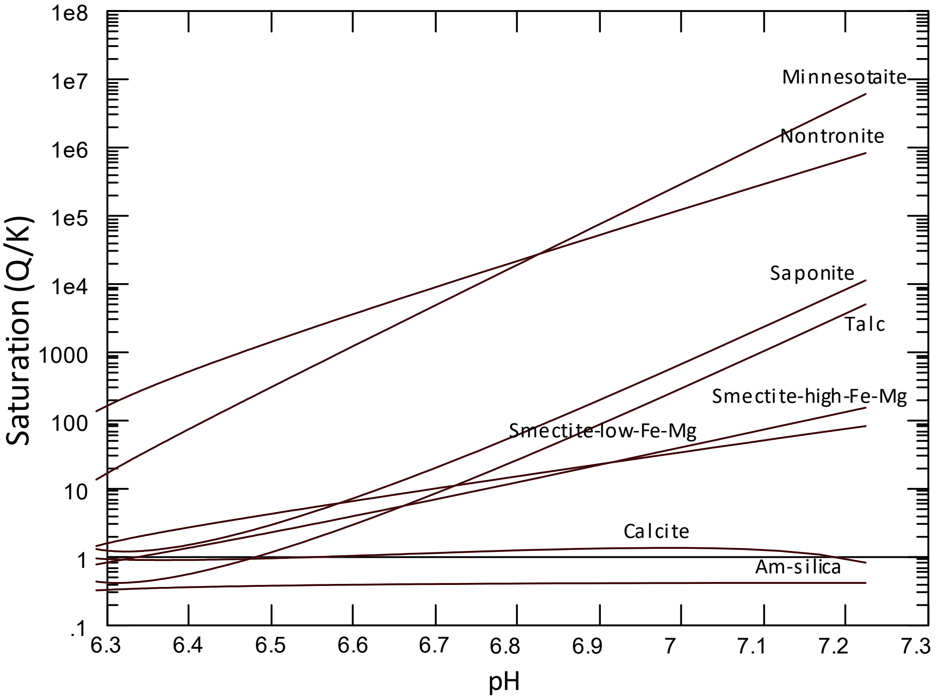


Figure 6: Plot of saturation indices (Q/K) for common scale-forming minerals such as amorphous silica, calcites and crystalline polymorphs (smectites) of scales observed in Heber, occurring during the HP flash process with exsolution of CO2 and decrease in temperature from 165°C to 127°C.

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