

## Interpretation of geochemical production monitoring data from well SJ4-1, San Jacinto, to indicate reservoir response to production

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### ABSTRACT

The chemistry of geothermal fluids discharged by wells gives insights on three main processes that may take place in the reservoir as a response to utilization: boiling, injection returns and groundwater incursion. The latest two reservoir processes are likely to cause cooling and, consequently, reduced energy available for electricity production. Enhanced boiling in producing aquifers can result in increased mineral precipitation potential and, hence, reduced permeability and well output.

Chemical composition of San Jacinto reservoir fluid was computed using the WATCH program (Bjarnason, 1994) based on component concentrations measured in water and steam samples collected from surface pipelines. In the calculations, it is assumed that no transfer of heat nor mass occur on the way of fluids from the reservoir to surface (Arnórsson et al., 2007). The selected reference temperatures are based on downhole measurements and quartz geothermometry.

In this study, geochemical production data of well SJ4-1 at San Jacinto, Nicaragua, collected since 2005 is reviewed as an attempt to identify physical and chemical processes possibly taking place in the producing aquifer. Well SJ4-1 is one of the wells that have the longest production history in San Jacinto with relatively stable output since initial production. It is considered to be fed by a shallow liquid aquifer, located at around -500 masl with an initial temperature of 275 °C. Reservoir tracer testing conducted in 2012 - 2013 has indicated this aquifer to be influenced by injection return from the system southern part. For the abovementioned features, study of well SJ4-1 is of special interest. The present analysis focuses on revising data on Chlorides (Cl), Boron (B), Silica (SiO<sub>2</sub>), Sodium (Na), Potassium (K), Non-Condensable Gases (NCG), Geothermometry, and Total Discharge Enthalpy as a function of time.

Different periods in the production history of San Jacinto reservoir are marked with a different dominant reservoir process, including boiling, injection return and shallow boiled water inflow, as a result of the production/injection strategy adopted.

### 1. INTRODUCTION

The concentration of some chemical components of geothermal fluids is directly affected by reservoir/aquifer temperatures. These components are known to be *reactive* and tend to equilibrate with minerals in reservoir hosting rocks. Examples of constituents that are generally tightly controlled by temperature are SiO<sub>2</sub>, Na, K. Cooling will be reflected in decreased SiO<sub>2</sub> concentration and increased Na/K ratio. Another group of chemical constituents of geothermal fluids are considered to be non-reactive or *conservative*. They do not tend to equilibrate with geothermal minerals and their concentration is not controlled by aquifer temperature. These components are used as tracers and provide information on the source of the fluid. Examples of this type of components are Cl and B (Arnórsson, 2000).

Enhanced boiling may be induced in producing aquifers if depressurization is high (i.e. extraction rate higher than recharge). As a result of boiling, the total discharge enthalpy of a well increases (developing of excess enthalpy), which is good in terms of energy availability. However, on the other hand, boiling can result in minerals precipitation in the aquifer and reduced permeability.

Peripheral non-geothermal (fresh) groundwater incursion in addition to shallow boiled brine inflow to the producing reservoir may occur due to depressurization caused by fluids extraction.

Injection return, if moderate, is considered to be good since it represents recharge, however, significant cooling may be caused by excessive inflow of injected brine into production zone.

Injection returns and groundwater incursion involve mixing of waters that have different chemical composition. Rejected brine is a boiled water and, therefore, it has higher concentration of dissolved solids, Cl and B in addition to lower concentration of gases than reservoir geothermal water. Therefore, if injection return to production zone is taking place it will be reflected in increased concentrations of conservative components (i.e. Cl and B) and decreased gas content in producer wells discharge. Shallow boiled brine and injected brine may have comparable chemistry, thus, resulting in similar observed changes. On the other hand, fresh non-geothermal water is diluted (low chloride). Ingress of this type of water to producing aquifer will be noticed by a decline in Cl content.

## 2. RESULTS

Figures 1 to 5 below show the concentration of selected components and estimated temperatures in the SJ4-1 producing aquifer as a function of time. Also shown are calculated average steamfield and SJ4-1 well total discharge enthalpies (Figure 6). Important operational events considered to affect the geochemical and thermodynamic characteristics of the aquifer are displayed in the Figures.

Since early production in 2005 up to date, the SJ4-1 aquifer temperature has decreased and its Cl content has increased (see Figures 1 and 2). Cooling is reflected by geothermometry and well logging data (*Magdalena Pérez, personal comm., 2014*). Boron and Na concentrations (Figures 3 and 4) show similar patterns to that of Cl (despite of greater scatter in Boron data), thus, supporting conclusions that can be made based on Cl chemistry. Gas concentration in total discharge shows early declination but an increasing trend in the last two years (Figure 5).

Average steamfield total discharge enthalpy exhibited minor variability from 2005 to 2011. Changes are attributed to SJ9-1 and SJ9-3 connection to the production system. Since 2012, steamfield enthalpy shows higher variability due to new wells brought into production. SJ4-1 total discharge enthalpy estimated by TFT shows small variability. Estimated values range from 1145 to 1245 kJ/kg.

As mentioned above, cooling and Cl increase may be caused by injection return. Another process that could originate these changes is shallow boiled water inflow. IncurSION of shallow fresh (diluted) groundwater is not considered to be occurring since it will be reflected in reduced Cl content.

A closer look of selected periods and consideration of important operational events allows a more detailed identification of geochemical evolution and potential reservoir process. This is described in Sections below.

### 2.1 June 2005 - April 2008: Start of production

#### Observed changes:

(a) Moderate cooling, (b) significant Cl content increase, (c) considerable gas content decrease, (d) nearly constant steamfield total discharge enthalpy.

#### Remarks:

Figure 6 shows approximately constant steamfield total discharge enthalpy during this period. Only wells SJ4-1 and SJ5-1 were under production at that time. It is assumed that discharge enthalpy of well SJ5-1 was nearly constant based in its stable production parameters and chemistry. Consequently, it is considered that SJ4-1 discharge enthalpy was also constant.

Constant discharge enthalpy, decreased gas content and increased Cl (and B, Na) concentrations in total discharge suggest that focused boiling in the SJ4-1 feeding aquifer is not likely to have occurred during this period.

Separated brine was injected into well SJ6-1 from July 2005 to March 2008. If injection return is considered to be the dominant process responsible for the observed chemical changes in SJ4-1, it implies that there was a significant connection between these wells. Steam condensate was injected into well SJ6-1 from January to June 2012. No significant changes were observed in Cl content in the SJ4-1 deep liquid (no dilution) and therefore, connection between SJ6-1 and SJ4-1 is probably minimal.

Finally, shallow boiled water inflow might have originated the noticed chemical/thermodynamic patterns observed during this period. This process could be induced in the aquifer as a result of depressurization by initial exploitation. In fact, it is noticed that more marked trends for Cl and gas chemistry are observed from June 2005 to late 2006, but stabilization is noticed since mid-2007. Thus, the observed chemical changes may be explained by initial production and depressurization.

### 2.2 April 2008 - December 2011

#### Observed changes:

(a) Moderate cooling, (b) sharp Cl content increase from April to October 2008 followed by nearly constant Cl concentration since 2009, (c) sharp gas content increase from April to October 2008 followed by a stabilized trend since 2010, (d) increased steamfield total discharge enthalpy from April to October 2008.

#### Remarks

Sharp Cl concentration rise noticed from April to October 2008 in addition to continued cooling suggest increased injection return caused by switching injection from well SJ6-1 to SJ10-1. Nonetheless, this is inconsistent with observed gas content increase during the same period. The reason for the augmented gas concentration in deep liquid is not completely understood, however, it is considered this process to be associated to well operational condition.

During late June 2008, well SJ9-1 was brought into production and well SJ4-1 was throttled to 45% (*Leonel Poveda, personal comm., 2014*). Well SJ4-1 was gradually opened back to 100% until May 2010. As a result of well throttling, significant variations in WHP were observed compared to those measured in 2007 (Figure 7). It is possible that observed increased gas content in samples collected on October 2008 and November 2009 is an effect of well throttling, thus, causing aquifer recharge and gas accumulation.

Increased steamfield discharge enthalpy observed in 2008 is attributed to SJ9-1 cut-in.

Despite sharp Cl content rise in 2008, it is seen that this parameter remained nearly constant from 2009 to December 2011 (even until mid-2012). It is accordingly concluded that chemical patterns noticed during this period were produced by moderate injection return from well SJ10-1 into SJ4-1 producing aquifer. Reservoir tracer testing confirmed a northward movement of SJ10-1 injected brine towards the SJ4-1 producing zone. Injected brineflow to southern wells has increased (approximately duplicated) since February 2013, thus, it is expected that injection return is higher at present.

### **2.3 January 2012 - August 2014: Increased fluid production and injection**

#### Observed changes:

(a) Considerable cooling, (b) nearly constant Cl content with slight increase since May 2013, (c) increasing gas content, (d) relatively stable discharge enthalpy with slight increase in mid-2013.

#### Remarks

This period is marked by a significant increase in steamfield total fluid production (Figure 8). In addition, injected brineflow into southern wells was augmented from ~300 to 700 tph in February 2013 (*Leonel Poveda, personal comm., 2014*). Observed aquifer temperature and Cl concentration trends suggest moderate injection return during 2012, with possible intensification since mid-2013 due to increased injection into southern wells SJ1-1 and SJ10-1.

However, the above statement is inconsistent with increasing gas content in total discharge since early 2012 (see Figure 3). As previously mentioned, gas content in SJ4-1 total discharge would be expected to decrease if only affected by injection return.

It is interesting to note that Figures 3 and 6 show comparable patterns for enthalpy and gas content in SJ4-1 total discharge during the last two years. Both parameters exhibit a slight increase from September 2012 to May 2013. These observations indicate that boiling could have occurred at least in a minor degree. The noticed increase in total discharge enthalpy despite of measured cooling in producing aquifer (developing of “excess enthalpy”) supports this conclusion.

### **3. CONCLUSIONS**

- Since early production in 2005 up to date, the SJ4-1 aquifer temperature has decreased considerably. Cooling is reflected by geothermometry and well logging data.
- Geochemistry of SJ4-1 fluids indicates that since initial production three reservoir process are likely to have occurred: shallow boiled water inflow, injection return and boiling.
- Different periods in the production history are marked with a different dominant reservoir process, as a result of the production/injection strategy adopted.
- Shallow boiled water inflow could be induced in the aquifer as a result of depressurization by initial exploitation, especially during the first two years.
- Moderate injection return from southern well SJ10-1 into SJ4-1 producing aquifer has occurred since 2008. It is expected that injection return is higher at present since injected brineflow to southern wells was nearly duplicated in early 2013.
- Boiling has probably taken place in the SJ4-1 feeding aquifer, especially in the last two years, when the total produced fluid from the steamfield has been significantly increased. The extent of boiling is considered to be affected by the rate of fluid extraction, natural recharge and injection return. The latest two processes may preclude enhanced boiling to occur.
- Continuous geochemical monitoring, as well as periodic reservoir tracer testing, are very important to identify different reservoir process and to evaluate their relative contribution in the observed cooling in the San Jacinto shallow aquifer since initial exploitation.

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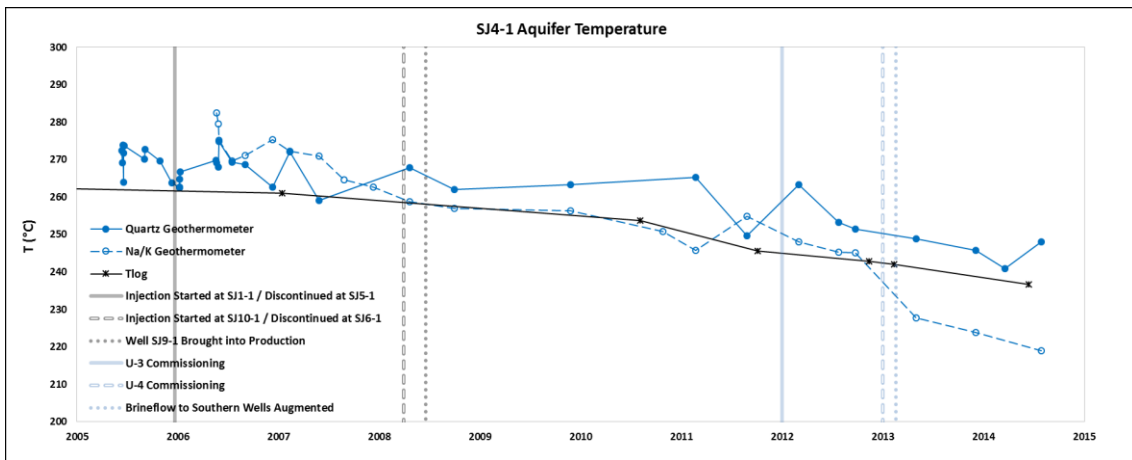


Figure 1: SJ4-1 aquifer temperature 2005-2014.

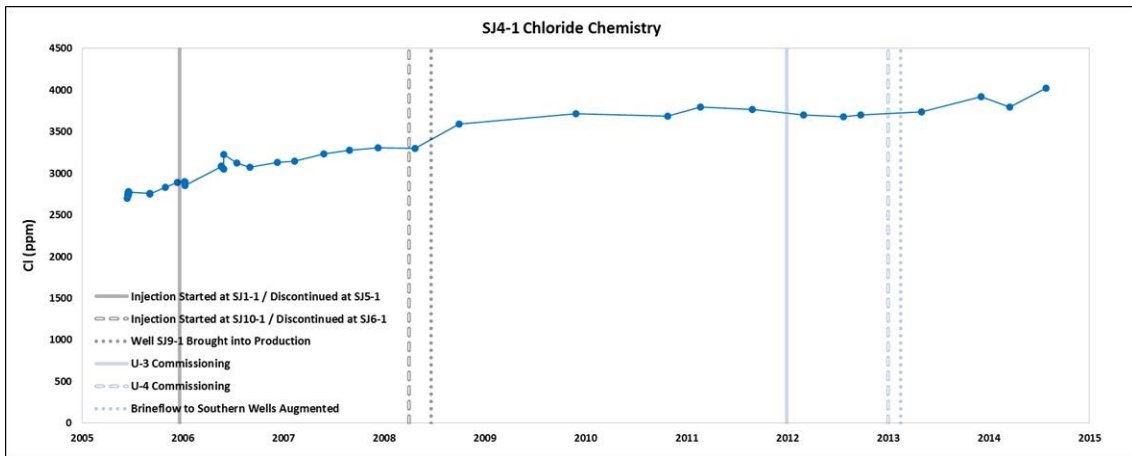


Figure 2: SJ4-1 chloride chemistry 2005-2014.

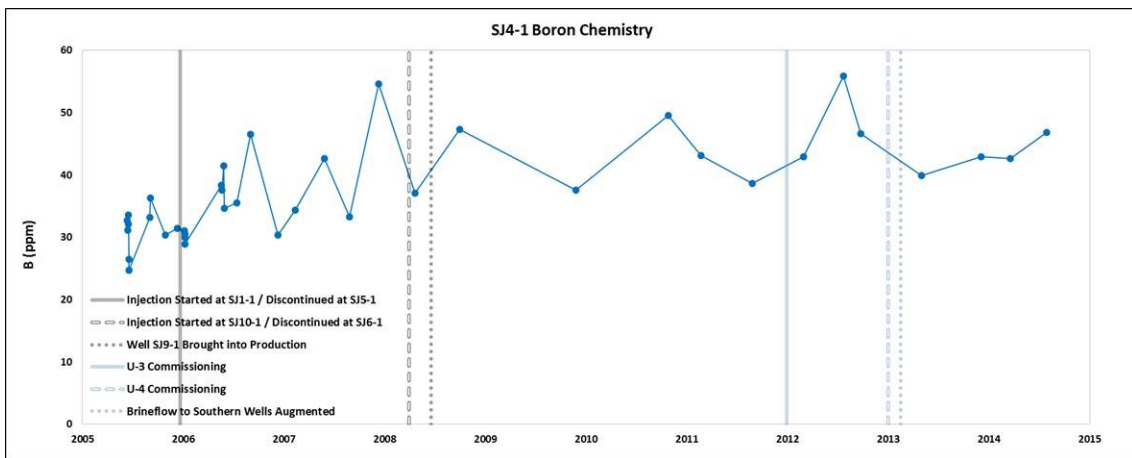


Figure 3. SJ4-1 boron chemistry 2005-2014.

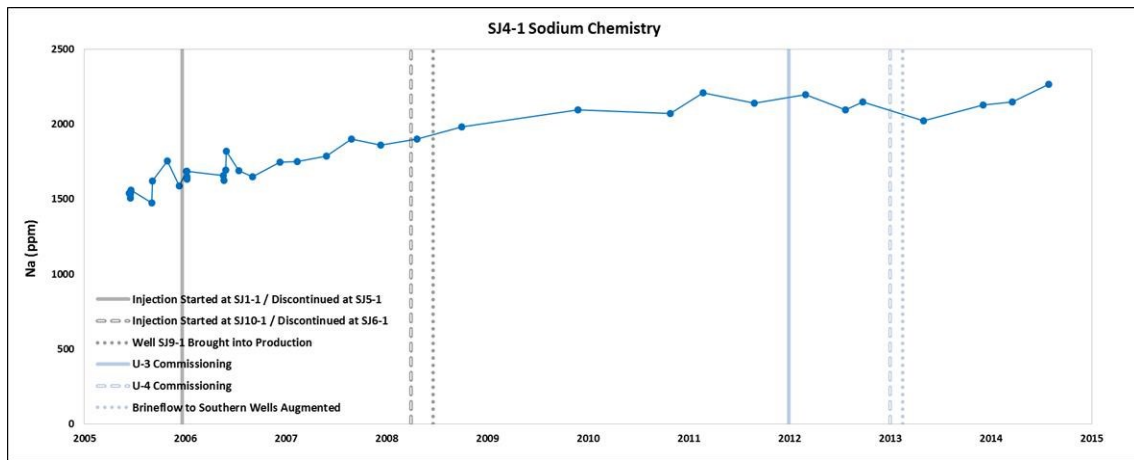


Figure 4. SJ4-1 sodium chemistry 2005-2014.

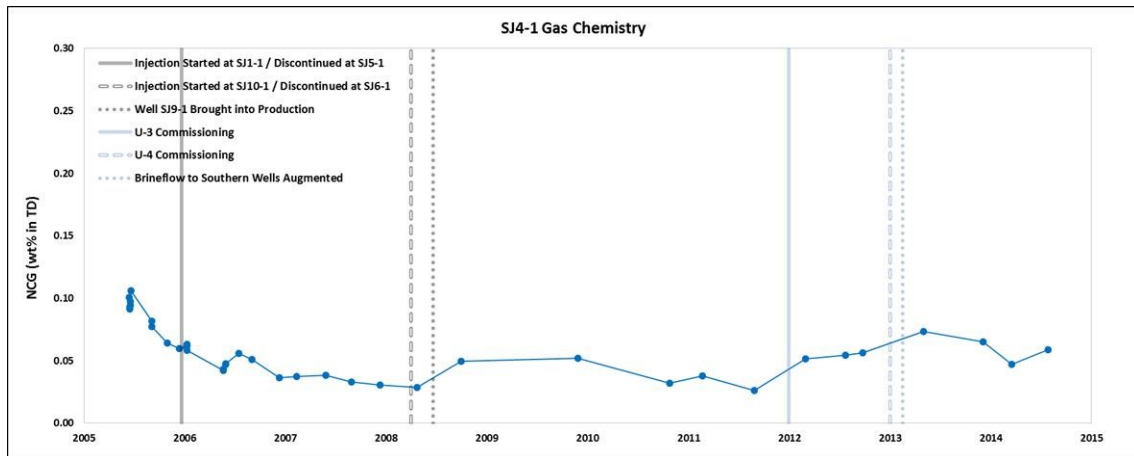


Figure 5. SJ4-1 gas chemistry 2005-2014.

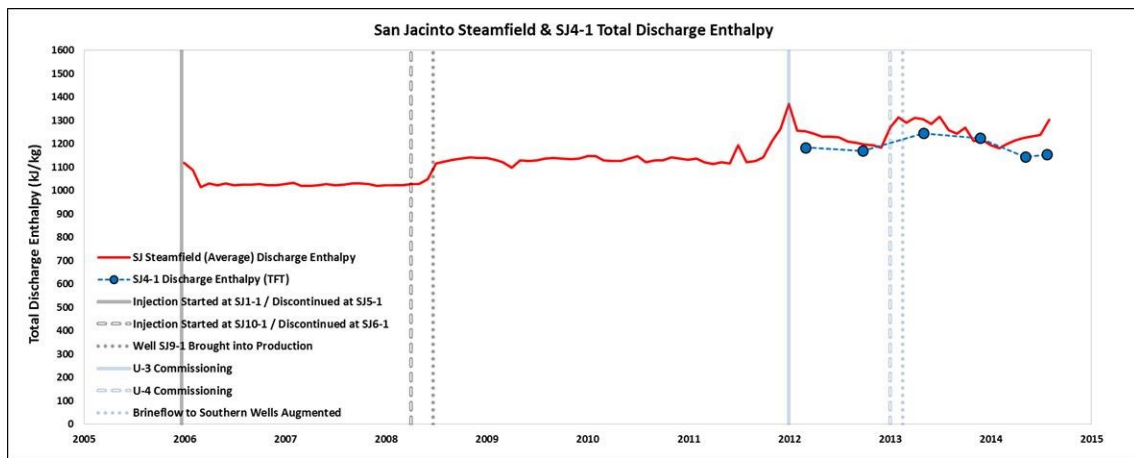


Figure 6. San Jacinto steamfield and SJ4-1 total discharge enthalpy 2005-2014. Steamfield discharge enthalpy calculated based on steam and brine flows presented in O&M Management internal reports (Leonel Poveda).

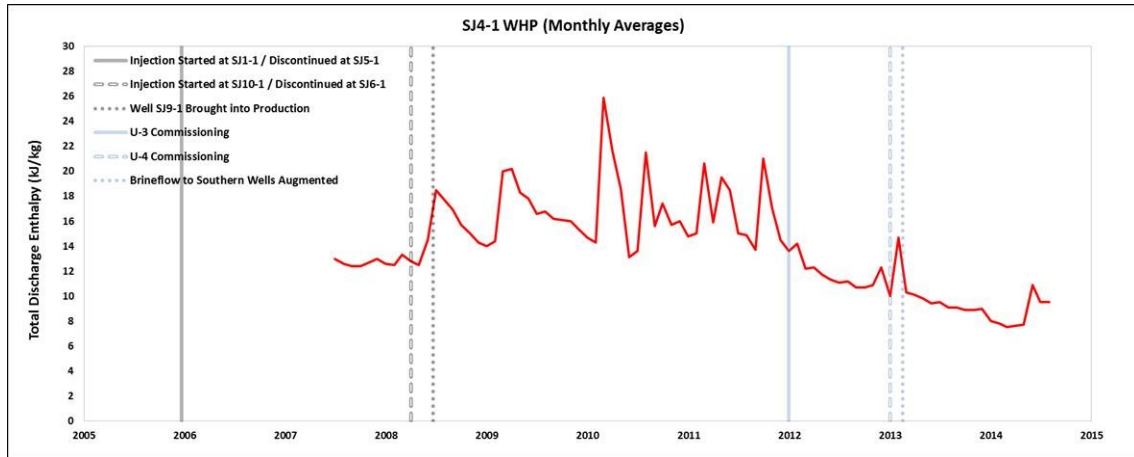


Figure 7. SJ4-1 WHP monthly averages 2005-2014. Source: O&M Management internal reports (Leonel Poveda).

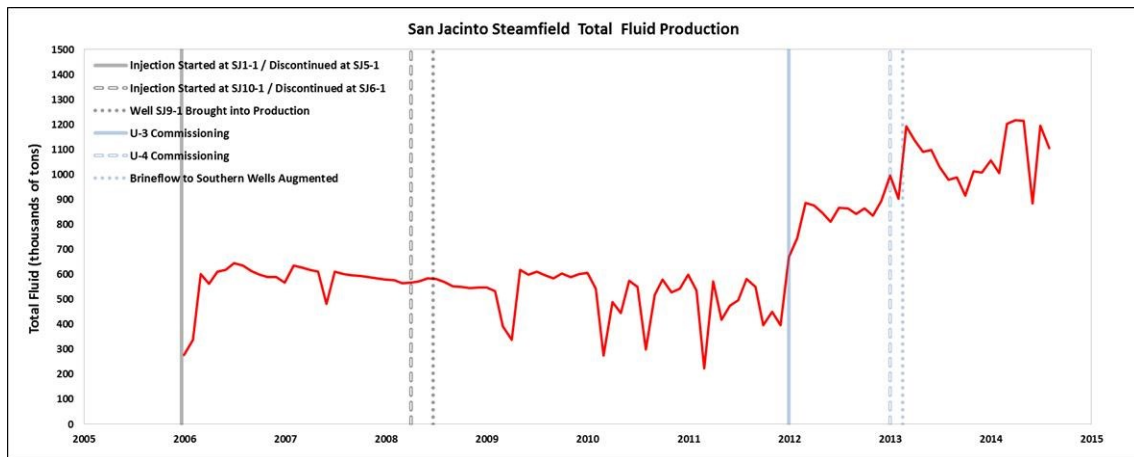


Figure 8. San Jacinto steamfield total fluid production 2005-2014. Source: O&M Management internal reports (Juan Escalante, Leonel Poveda).