VARIATIONS OF THE INFERNO CRATER LAKE CYCLES, INSIGHTS FROM NEW DATA

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ABSTRACT

Crater lakes in active volcanic vents are unique features providing an insight into the state of natural geothermal systems. Inferno Crater Lake, in the Waimangu Geothermal area near Rotorua, has regular cycles in its temperature and lake level, varying from 12 to 56 days in length. These cycles do not seem to be related to the magmatic activity of Okataina Volcanic Center, rather representing an unstable heat convection system under the lake. The cycling patterns show four different types of cycle, based on sixty-five years of data. Each kind of cycle has a specific behavior of lake temperature and water level. Type II is the most common cycle with a mean length of 33.2 days and one overflow. When successive overflows happen, we have a cycle of type I, with an average length of 56.1 days. The lack of overflow defines the other two types; type III for short cycles lasting about 12.0 days, or a type IV whose mean length is 30.0 days. Even if types I to III show some tendency to repeat, no features of the cycle can be used to predict which type will occur next. All the types of cycle start with the same rapid rise of lake temperature and level. Heavy rainfall and seismic and hydrothermal events do not generate any particular type of cycle. Finally, the regular oscillations which occur during a cycle with an average period of 2.2 days could be generated by accumulating steam pressure in a volume under the lake, similar to a geyser mechanism.

1. INTRODUCTION

Geothermal activity occurs in areas where water is heated in the subsurface before finding its way out through open passages to the surface. The hot water rises and discharges at the surface as geysers or hot springs, generally using the fractures and natural jointing. Sometimes crater lakes are formed on active volcanoes and can be unique features associated with hydrothermal systems. They offer an insight into the hydrothermal systems, allowing the study of the mechanism and interactions of the water with magmatic sources.

Crater lakes sometimes show temperature and level cycles which are not due to magmatic activity. Inferno Crater Lake (Figure 1) in New Zealand is an example of such periodic behavior. It occupies a crater in a former rhyolite dome shaped by one of the vents formed during the eruption of Mount Tarawera in 1886. The Tarawera Rift eruption created a 17-km-long *en echelon* fracture where craters extend from NE of Wahanga Dome in the Tarawera

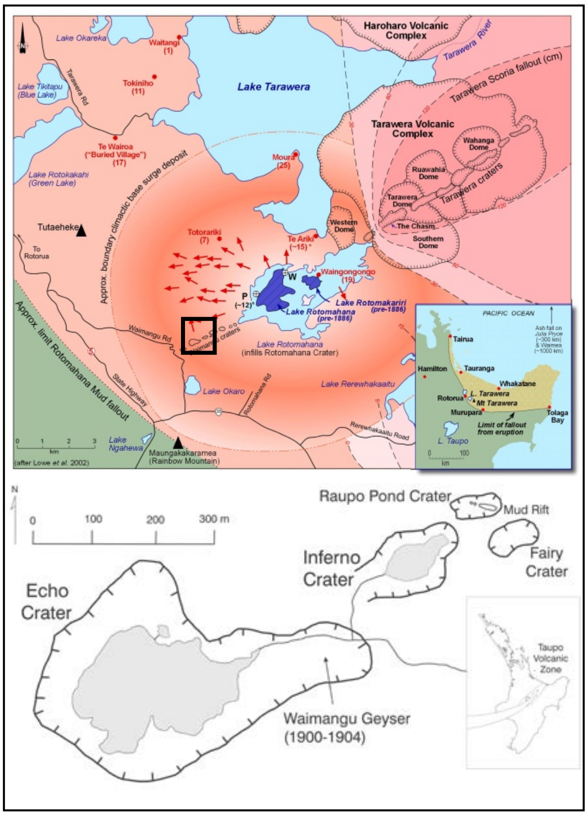

Figure 1: Map of Tarawera area showing locations of the main craters of the 10 June 1886 fissure eruption across Tarawera Volcanic Complex, Rotomahana Crater (including pre-eruption lakes Rotomahana and Rotomakariri), and Waimangu craters (after Lowe *et al.*, 2002). Map of Waimangu hydrothermal area focusing on Echo Crater and Inferno Crater area, Taupo Volcanic zone, New Zealand (Vandemeulebrouck et al., 2008).

Volcanic Complex to the Southern Crater at Waimangu (Scott 1994).

Inferno Crater Lake is a hot acidic lake, whose temperature varies between 40 to 80°C, the variations being strongly related to changes in water level of Inferno. The water level fluctuates through time and regularly reaches a level where it overflows into a small channel South-East of the lake. Inferno's cycling period is short and well documented, providing a long time period with many cycles to investigate the features of the cycles. Previous studies of Inferno Crater Lake (Scott *et al.*, 1994, Vandemeulebrouck *et al.*, 2005 and Vandemeulebrouck *et al.*, 2008) were focused on early data (1971 to 1990) which were only daily averages of temperature and water level, conducted by various research initiatives. Since the 1990s, more regular measurements (every 15 min) have been recorded, showing the cycles in detail and highlight four different patterns.

2. DESCRIPTION OF THE CYCLES

The temperature of Inferno Crater Lake and its water level vary together (Scott, 1994); the lake level increases with the increase of the temperature in cycles lasting from 12.0 to 56.1 days in average. All cycles start from low temperature (38-52°C) and level (7.2 to 4 m below overflow) and rise rapidly. The temperature shows constant oscillations between 60 and 70°C while the water level presents the same oscillations during the increase. Usually, the lake level reaches a point where it overflows into the outlet stream, and at this moment, the temperature of the lake is above about 70°C. The cycles end with a rapid recession, even though overflows are not always observed during a cycle. A detailed analysis of the temperature and water level records showed that the cycles could be divided into four different types, based on the pattern of rapid temperature and level variations within the cycle.

Cycles of type I were first observed in 1986 and 1990 (Scott 1994) but several more occurred between 2007 and 2009 (10 out of 14) with a length ranging from 37.6 days to 66.8 days (56.1 days in average). One very long cycle began on the 22nd Oct 2005 though, and lasted for 78.6 days. Of the remaining cycles, one happened in 2006 and the two latest ones were in 2010 and 2013. This cycle type is defined by one distinct peak of temperature matching with the first overflow of a series, usually gathering five overflows in average. In average, 4.1 days separate the overflows while the lake level increases by 5.5m during those cycles, with values ranging from 4.3 to 7.3m.

Considering the period from 2005 to 2014, few cycles of type II happened before 2012 (3 out of 14), the rest were all between 2012 and 2013 (11 out of 14). Those cycles usually last for 33.2 days and range from 27.2 to 43.8 days. The peak of temperature follows the periodic oscillations of the temperature, ending the cycle, and corresponds to the unique overflow of the lake. During these cycles, the water level increases by 4.8 m on average with values between 3.9 to 6.7 m.

Before 2013, the thermocouple was not in the water, so did not reach stream temperature; it was only an indicator of the overflow. Therefore, based on data since 2013, the temperature of the overflow stream is in the range from 70 to 77°C for both Types I and II.

Half of the type III cycles occurred during the first 7 months of 2010 (11 out of 21) with the other half between 2012 and early 2014 (10 out of 21). These cycles are characterized by a short length, 12.0 days on average, with values ranging from 8.4 to 16.1 days. The water level increases by 2.9m on average, reaching a mean depth of 3.1 m below overflow (values ranging from 5.3 to 2.1 m below overflow) and never goes beyond. The cycle is shaped by a low peak of temperature, ranging from 61.6°C to 71.4°C with an average of 66.3°C.

The six cycles of type IV are spread between 2010 and 2013 and last for 30.0 days on average with lengths ranging from 26.6 days to 36.1 days. Those cycles are very similar to the cycles of type I, but they are shorter and only present the periodic oscillations that can also be found in cycles of type I and II. There is no distinctive peak of temperature and like type III, no overflow happens even though the water level reaches 0.5 m below overflow on average and then drops as the cycle ends.

Based on 90 cycles from 1971 to 2014, probabilities to determine the type of the following cycle have been calculated (Table 1). Type II is the most common type

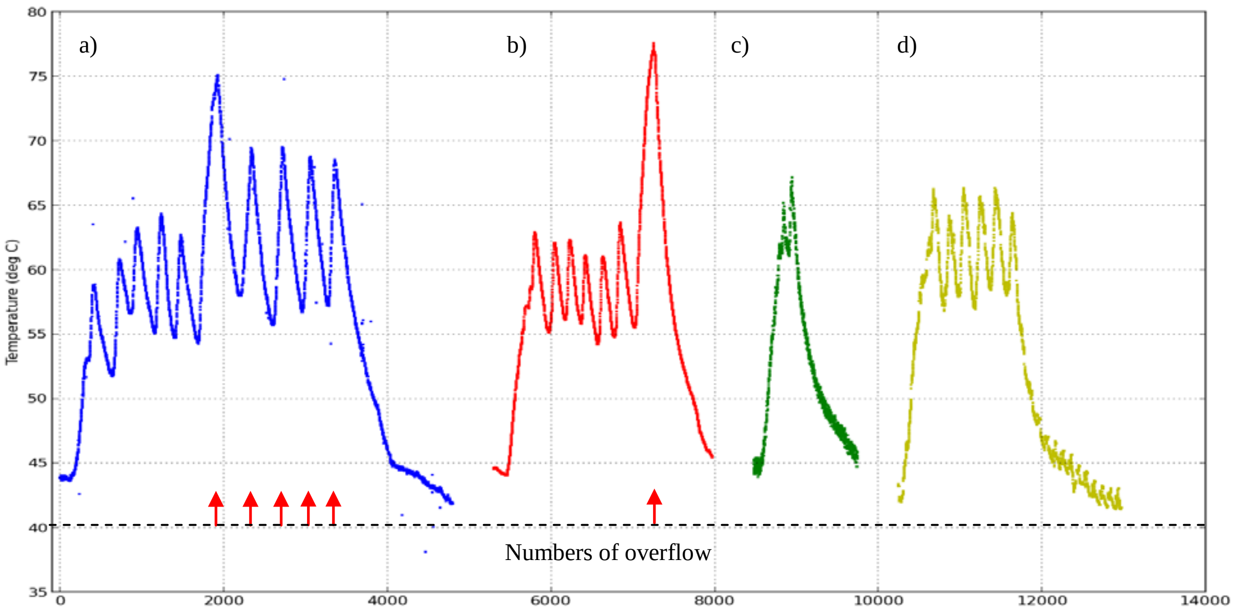

Figure 2: Example of the evolution of the lake temperature for each type of cycle with overflows shown by arrows. a) Type I shows periodic oscillations before and after the main peak while b) type II ends after the maximum of temperature. A short cycle without overflow is c) type III whereas periodic oscillations but no overflow is d) type IV.

while type I are either absent or unclear before 2005. Also, there is a tendency for type I to III to repeat, while type IV seems to generally precede type II.

Cycle Type t+1 / Cycle Type t	I	II	III	IV
I	66.7	8.3	25.0	0
II	7.0	65.1	23.3	4.6
III	4.2	25.0	45.8	25.0
IV	0	54.5	18.2	27.3

Table 1: Probabilities (in percentage) to determine the type of the next cycle knowing the current one.

3. MECHANISM OF THE CYCLES

3.1 Comparison with the geyser cycles

A porous media including open channels that may have initially been produced by hydrothermal explosions forms a potential plumbing system for a geyser. Several stages define geyser eruptions (White, 1967): (1) an initial overflow of liquid water at temperature less or equal to the local boiling point; (2) fountaining, liquid-dominated discharge; and (3) steam-dominated discharge of gradually decreasing intensity. In other words, when the steam present in the geyser enters a region, it increases the pressure in the porous media up to the hydrostatic pressure above which the steam starts to bubble towards the surface. White (1967) also suggests the presence of subterranean eruptions, in which no water reaches the surface. Several geysers seem to have these between their surface discharges.

Experiments have been conducted (Vandemeulebrouck *et al.*, 2005) to reproduce hydraulic systems of Inferno Crater Lake. The hydrothermal system can be modelled by 3 layers: the top layer would be the lake standing above a porous or fractured medium saturated with liquid. A two-phase layer formed by liquid and steam lays under the liquid layer as shown in Figure 3. Regarding Inferno, this two-phase layer seems to be produced by an accumulation of fine material acting as a porous media, in which surface tension stops the steam from producing big bubbles and rising rapidly. Thus steam and water goes around each other, with the first one going up and the second one going down.

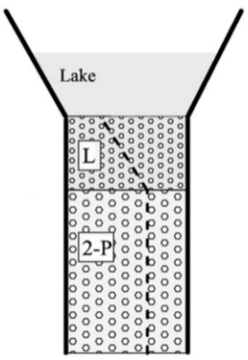

Figure 3: Schematic diagram of a 1-D heat pipe model (Modified from Vandemeulebrouck et al., 2008).

The steam contained in the two-phase layer does not entirely reach the surface, it nearly all condenses on the way, but produces a high heat flux. Some resistivity measurements (Legaz et al., 2009) show that in the case of Inferno, a discontinuity at the interface between the two-phase layer and the liquid layer allows the steam to push the lake upward, but not enough to produce a geyser. The distribution of the resistivity indicates that there might be a cavity or a more porous medium surrounding the conduit which catches part of the steam, stopping it from discharging at the surface.

3.2 Periodic oscillations

The periodic oscillations observed in the type I, II and IV are very similar and can be analyzed by applying a *Fast Fourier Transform (FFT)* to the selected signal which is here the temperature. Plotting $|FFT|^2$ as a function of the frequency gives the analysis in the spectral domain. We only considered frequencies between 0 and Nyquist Frequency $f_n = 0.5f_s$ where f_s is the sampling rate; frequencies greater than Nyquist Frequency are negative and thus are not representative in this study. Eighteen cycles of type I, II and IV between 2012 and 2014 have been selected to analyze their periodicity in the time domain. The period is given by the maxima of each plot. Figure 4 represents the maxima of the analysis in the time domain, where the average period of the oscillation appears to be 2.2 days in average (about 52 hours and 19 minutes). This period can hardly be related to daily variations, tidal effects or human activity. A possible explanation would be the presence of a hydrothermal feature like a cavity acting as a sort of failed geyser; accumulating steam and then discharging it into the lake could generate subterranean eruptions as suggested by White (1967).

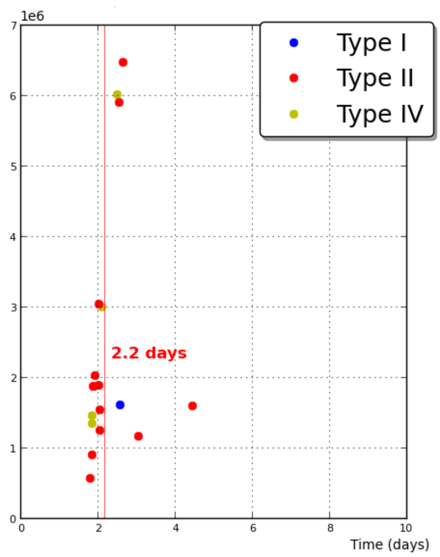

Figure 4: Maxima of the 18 cycles of type I, II and IV from 2012 to 2014 used to determine the period of the oscillations.

3.3 Influence of external factors

In order to better understand the mechanism of the cycles, we compared the cycles with different external factors which are known to affect geothermal areas, including rainfall data, seismic and volcanic activities and in this case the influence of another crater lake in the immediate environment, Frying Pan Lake. Frying Pan temperature and discharge are known to be influenced by the rainfall (Scott 1994), therefore it could also affect Inferno's cycles. However, our comparison of rainfall at Okaro at Birchalls (2km South of Waimangu) did not see a connection with the type of cycle. Neither the cumulative rainfall during a cycle nor the average rainfall from the preceding cycle influences the type of cycle. The rainfall does not seem to have an impact on the cycle mechanism. Various seismic and hydrothermal events happened around Okataina Volcanic Area which may have influenced the temperature cycles of Inferno Crater Lake. Because most of the significant events occurred between 1971 and 1990, we focused at the daily data which were recorded at Inferno Crater Lake from 1971 to 1998. Only earthquakes of intensity higher than V in Waimangu have been used here. Indeed, earthquakes of lower intensity are very unlikely to have influenced the geothermal area. No clear relation can be found between the small seismic events and the behavior of the cycles. In other words, the earthquakes do not generate a particular type of cycles according to their intensity or magnitude. Vandemeulebrouck *et al.* (2008) focused on the Edgecumbe earthquake (M_L=6.3 and M_w=6.5) which occurred on 2nd Mar 1987 approximately 50 km north-east of Waimangu. The earthquake intensity at Waimangu was MM VI (*Modified Mercalli*). It had a normal mechanism and generated a change in the cycling period. Hydrothermal explosions also influence the period of the cycles, inducing shorter cycles. Nevertheless, daily averages data do not show the cycles clearly, keeping from determining the cycle type. Therefore, those observations need to be confirmed by new seismic and hydrothermal explosions, while there are 15-min data recordings.

Previous studies (Llyod 1973, 1974, Scott 1991, 1994) demonstrate several relations between Frying Pan Lake and Inferno Crater Lake among which is the inverse variation of the discharge of Frying Pan Lake with the water level of Inferno Crater Lake. Despite the similar length of temperature cycles in Inferno Crater Lake and Frying Pan Lake, those cycles are not in phase. This implies the absence of a direct hydraulic connection between the two lakes. Each cycle at Inferno begins with a very high discharge rate of Frying Pan Lake of about 127.9 L/s which ranges from 98.0 to 158.4 L/s and decreases to a minimal value of 91.4 L/s in the range 54.0 to 120.5 L/s. Then, the decrease in discharge ranges from 13.7 to 59.1 L/s with a mean value of 36.5 L/s. Although daily variations are present, the obvious relation between the two lakes shows that when the water level of Inferno Crater Lake increases during a cycle, the mean discharge of Frying Pan Lake decreases and the discharge reaches its highest rate right after the overflow of Inferno, when a new cycle begins.

4. PREDICTION

As there is no clear relation between the cycle type and external factors, we focused on the prediction of the cycle type, firstly by superimposing cycles in temperature (Figure 5). All types of cycles present a very similar initial rise which is not distinctive of any type. Then, all sorts of things

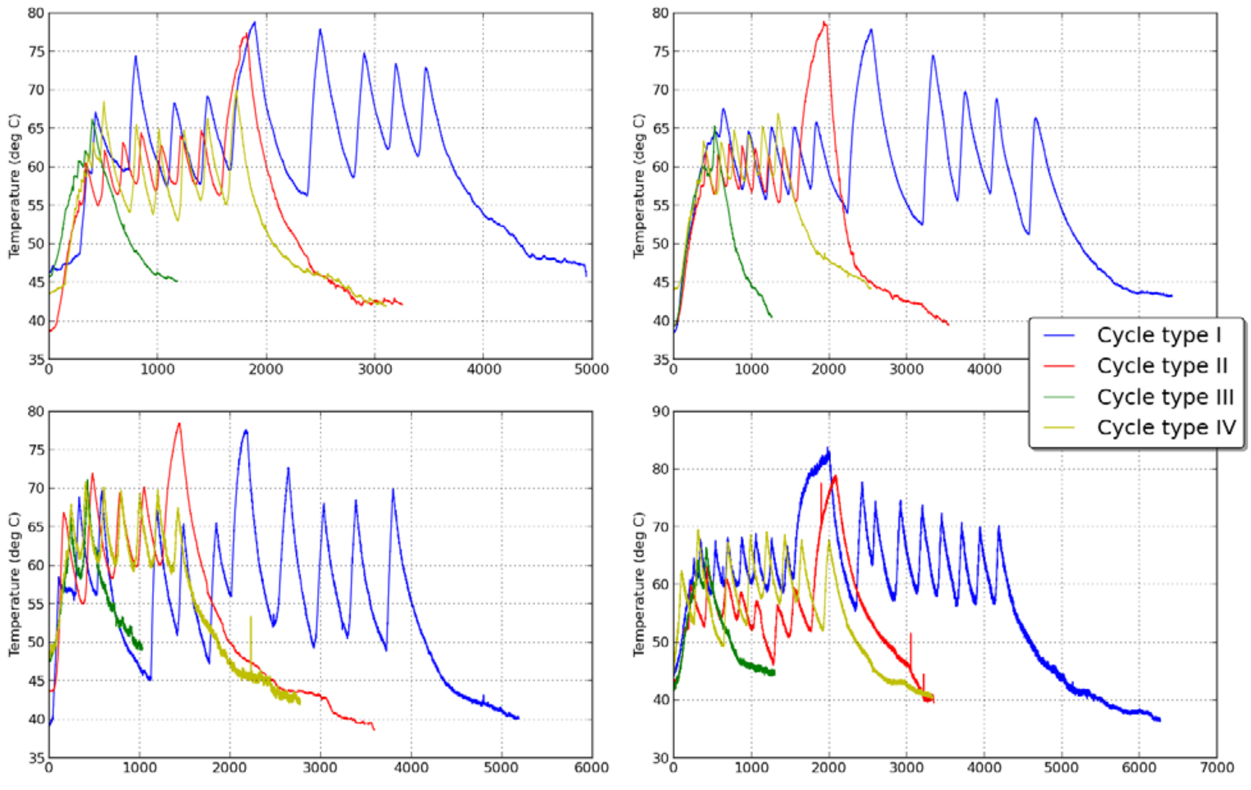

Figure 5: Examples of the different cycles superimposed, showing a very similar rise and then different patterns developing.

can develop. For types I, II and IV, the oscillations following the main rise cannot be characteristic of the type whereas the temperature variations of type III do not show any oscillations at all after the first rise. The preceding minimum temperature does not vary much, and as seen in Figure 6, there is no indication that its variations correlate with the type of cycle that follows. Therefore, any effect on the cycles must be from the water level of Inferno Crater Lake.

In contrast with the temperature, the initial water level shows some connections with the type of cycle that follows. On Figure 6 the initial water level for cycles of type I is between -5.8 to -5.2m below overflow with two exceptions: one cycle starts deeper and three start shallower. In the first case, the value cannot be totally trusted as it happened right after a gap in the records. For the second exception, the shallower values correspond to 3 cycles occurring during series of higher recessions. Regarding type II, the initial water level ranges from -4.9 to -3.9m below overflow with only one cycle whose value is deeper, which could be due to the general trend of the water level being lower during this period of time. Cycles of type III show an initial water level ranging from -7.2 to -4.7m below overflow. This is the widest range for an initial water level, thus it cannot be distinctive of type III, unlike ranges for type I and II. However, the initial water level for cycles of type IV is the same as for type I: from -6.0 to -4.9m below overflow. Even if cycles of both types I and IV come after deeper recessions of Inferno, there is no simple relation between the water level and what the next cycle does, as if deep recessions meant either lots of overflow or no overflows.

Figure 7 shows the correlation with each type of cycle and the minimum lake level at the end of the cycle; first depending only on the type of the previous cycle, then depending on both the cycle preceding and following the minimum of water level. There is a slight tendency for the minimum after type II to be higher than after other types consistent with the types tending to repeat and type II starting after a higher minimum.

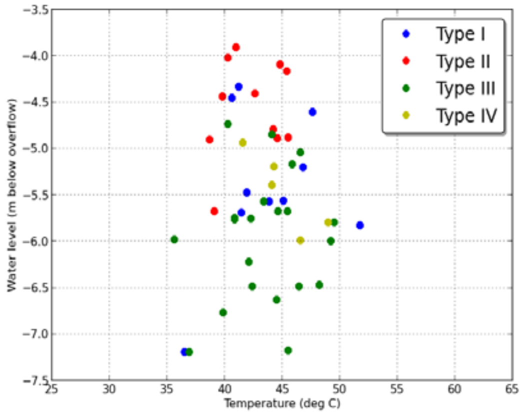

Figure 6: Initial temperature against initial water level for 62 cycles from 2007 to 2014.

5. CONCLUSION

Very few external factors can be considered to study the origin of the variations. Even so, the cycles of Inferno Crater Lake do not seem to be by affected by the regional rainfall and present little relation to the seismic and hydrothermal explosions. Vandemeulebrouck *et al.* (2008) showed how distant earthquakes and hydrothermal explosions can affect the cycling of Inferno based on daily averages. It would be interesting to witness the response as shown by 15-min readings of Inferno Crater Lake to local hydrothermal activity or strong shaking, but we have not yet had either since the equipment upgrade. Moreover, seismic and volcanic activities are not distinctive of any cycle type i.e., if any of those events happens, it could generate either a type II, III or IV (no data for type I during hydrothermal eruptions).

A general decrease of the cycle length is observed between 1971 and 2014 (Figure 8) with a reduction of 23.7% for type II, 23.5% for type II and 12.3% for type IV. This goes with shallower recessions of Inferno, around 7 m below overflow for 2005 to 2014, in opposition with 10 m below overflow between 1971 and 1998. Near Inferno, the

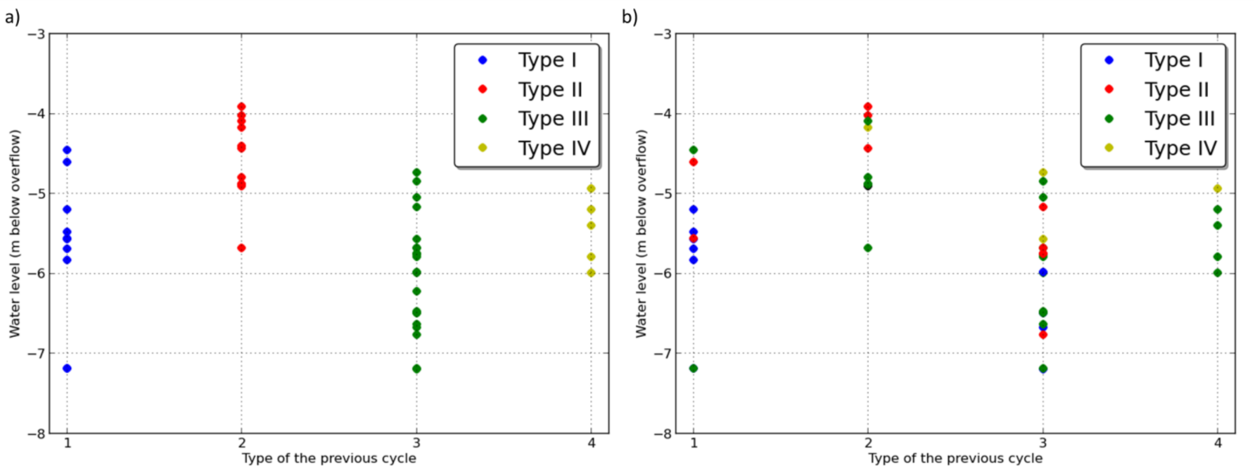

Figure 7: Correlation with each type of cycle and the minimum lake level at the end of the cycle. On a) the x-axis and the color show the type of the previous cycle while on b) the color represents the type of cycle following the minimum lake level.

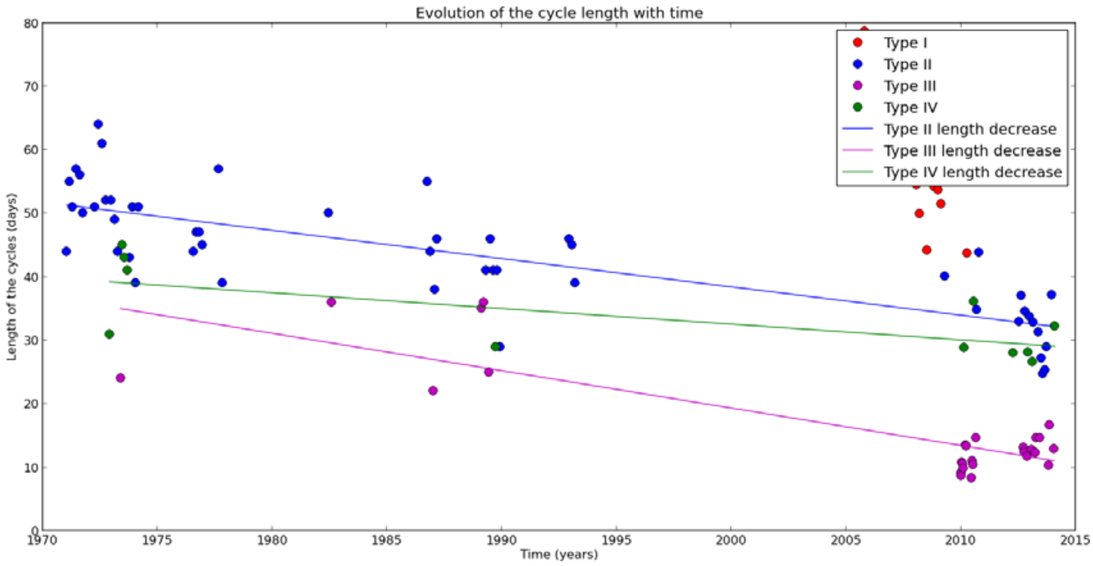

Figure 8: Evolution of the cycle length with time (1971 to 2014).

discharge of Frying Pan Lake displays an inverse relationship with both the water level and temperature of Inferno Crater Lake. The discharge tends to decrease varying from 100 to 120 L/s from 1971 to 1998, reaching 70 to 80 L/s from 2005 to 2014.

The state of Inferno Crater Lake before a cycle is not affected by the temperature, but by the water level. Type I and IV start after the same range of recession while there is no specific range of minimum lake level for type III. However, there is a tendency for type II to start after a shallower recession.

In conclusion, Inferno Crater Lake could be an aborted geyser as the steam pushes the water but cannot reach the surface. A change in the porosity around the main conduit could explain why the steam is only pushing the lake instead of discharging the water as a geyser. In order to confirm this hypothesis, further investigations could be undertaken: as a continuity of the project of Legaz *et al.* (2009), a 4-D resistivity profile focused around Inferno could be considered. Resistivity measurements could be repeated every week for six months in order to cover as many different cycles as possible and therefore analyze the movements of steam during the stages of the cycles. Besides resistivity, the underground of Inferno could be investigated with a Ground Penetrating Radar (GPR) to highlight the changes in material, the voids and cracks. Those projects could be difficult to undertake because the topography around Inferno is not flat and more importantly because of the thick vegetation surrounding the lake.

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