After Four Years of Ground Displacements Following LUSI Mud Volcano Eruption; Sign of its Ending Eruption

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Key words: Mud Volcano, Ground Displacement, GPS, exponential decay

SUMMARY

On May 29, 2006 a mud volcano started to form at Porong Sidoarjo East of Java Indonesia. It is further termed as LUSI Mud Volcano (LUSI = Lumpur Sidoarjo ; Lumpur mean mud in Indonesia language). Mud, water, and gas extruded massively and flooded the surrounding areas. The mud flow currently covers an area of about 7 square-km, covering several villages. About 40,000 people have been displaced and the mud volcano is still active after more than 4 years. The mud volcano seems to be unstoppable, and all the attempts to halt the mud eruptions have so far failed and never will be succesfully perhap.

The eruption of the LUSI mud volcano has triggered vertical (subsidence) and horizontal ground displacements. In the early development of mud volcano, GPS surveys results show that subsidence is occurring at rates of 0.1 and 4 cm/day surrounding the eruption area. In the areas closest to the mud eruption, the results indicated the existence of horizontal concentric vector displacements and circular depressions of vertical vector displacements around the mud volcano which is expressing caldera formation processes.

Today its already four years and even more since the first time of the eruption, and the record of ground displacements inffered from several last GPS surveys showing exponential decay pattern. It is an interesting pattern of displacements we believed. Since the displacement associated with the eruption, the exponential decay might be indicating or signing the ending of LUSI Mud volcano eruption. This paper will mainly explain these suggested situation in detail.

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1. LUSI MUD VOLCANO

On May 29, 2006 a mud volcano started to form at Porong Sidoarjo East of Java Indonesia. It is further termed as LUSI Mud Volcano (LUSI = Lumpur Sidoarjo ; Lumpur mean mud in Indonesia language). Mud, Water, and Gas extruded masively and flooding more than a kilometer areas. Since its extrusion day, the mud mixed water and gas has caused significant livelihood, environmental and infrastructure damages (Figure 1).

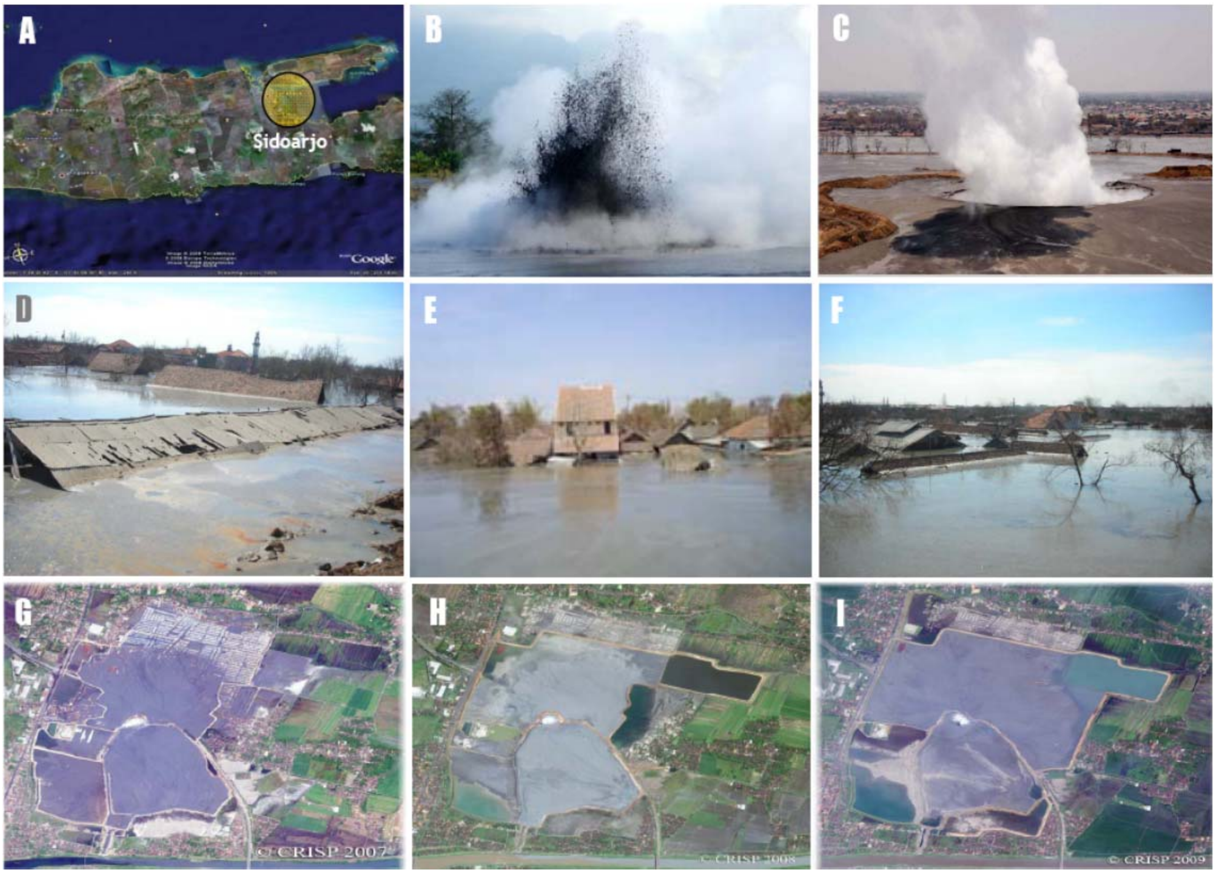

Figure 1 (a) LUSI mud volcano location, (b,c) LUSI mud volcano eruption, (d,e,f) scene of mud flooded, (g,h,i) map of flooded areas.

The volumes of erupted mud increased from the initial 5000 m^3/day in the early stage to 120,000 m^3/day in August 2006. Peaks of 160,000 and 170,000 m^3/day of erupted material follow earthquakes swarms during September 2006; in December 2006 the flux reached the record-high level of 180,000 m^3/day; and in June 2007 the mud volcano was still expelling more than 110,000 m^3/day (Manzini *et al.*, 2007). Latest information (after four years from eruption) showing 10,000 m^3/day erupted materials which is mostly dominated by water.

1.2 **Ground Displacement at LUSI Mud Volcano**

Considering the effects of mud loading, collapse of the overburden due to the removal of mud from the subsurface (eruption) and, land settlement caused by surface works (e.g. construction of dykes), etc., around LUSI mud volcano, ground displacements occurred immediately after the eruption. Latter on, the surface representation of displacement was also occurred such as crack on the wall, houses, street, bend on the rail ways, etc. On 24 November a gas pipeline exploded near the mud extrusion centre, killing several people. Part of ground displacement furher may explained the caldera formation processes is happening on LUSI Mud Volcano (Andreas *et.al*, 2009, 2009a, 2010). Caldera formation Processes is one of main processes of the birth and development of mud volcano. It Perform as a result of adaptation of subsurface extruded material (e.g mud, water, gas) to the surface following by surface collaps which is the next result performed typical morphology of caldera. Some research clearly show the relationship between loss of volume in the shallow subsurface and caldera collapse (e.g. Acocella 2006; Aizawa *et al*. 2006; Geyer *et al*. 2006).

2. GPS OBSERVATION AND PROCESSING

GPS observations, both in campaign and continuous mode were conducted to study ground displacement phenomenon following the birth and development of LUSI mud volcano; among cooperations of some institutions. Fivetheen GPS campaigns have been conducted between June 2006 and December 2010. On figure 2 we can see some documentations of GPS surveys in the field.

GPS surveys were performed on up to about 50 stations with set area over 10 kilometers rounding the center of eruption, using dual-frequency geodetic-type receivers, with observation session lengths of about 5-10 hours. GPS continuous subsidence monitoring was also conducted on some stations, started on 22 September 2006 to early 2007. Due to the change in mud coverage area, the numbers of observed GPS stations were different from survey to survey, and the observed stations could not always be the same. The locations of GPS stations were also restricted by the mud coverage and its progression.

Data processing of the GPS survey was conducted using the scientific GPS processing software Bernese 4.2 (Beutler *et al.*, 2001). In general, standard deviations of the estimated coordinates are in the order of several mm in both horizontal and vertical components. To derive the ground displacement information is simply by differencing the coordinates that has processed in each period of GPS surveys.

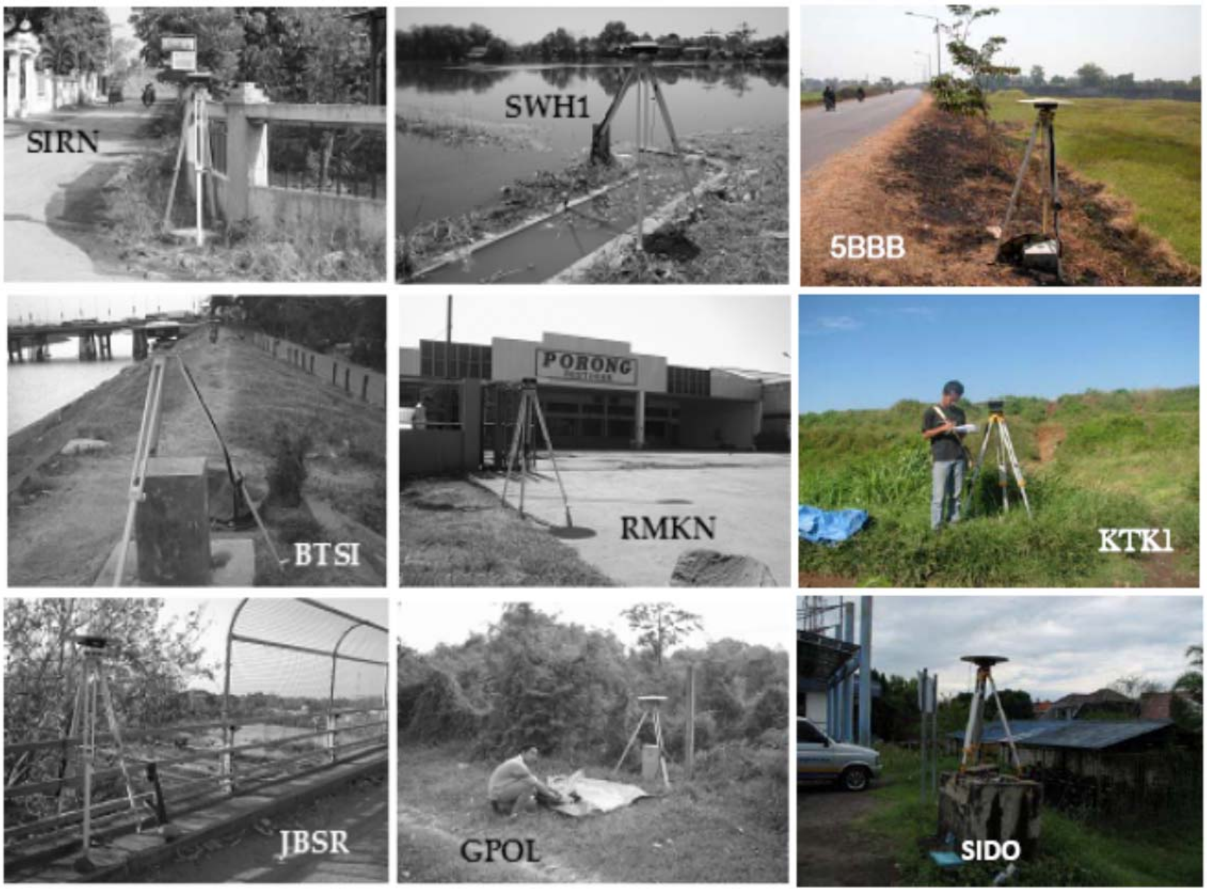

Figure 2 Some documentation of GPS survey in the field using dual-frequency geodetic-type receivers, with observation session lengths of about 5-10 hours.

3. RESULT OF GROUND DISPLACEMENTS

3.1 First year result

The GPS derived displacements from the GPS campaigns showed that the surface displacements in the mud volcano area of Sidoarjo have both horizontal and vertical components. In the first 4 months of mud extrusion it can be seen that the rates of displacements from data compilation and interpolation are in the order of 0,4 to 2,5 cm/day and increasing on the next 8 to 12 month later into 0,6 to 3,8 cm/day for vertical component surrounding the erruption site (see table 1). According to other result (Abidin, 2008) in several month after LUSI erruption, the rates of horizontal and vertical displacements were up to 2 cm/day and 4 cm/day, respectively; and vertical displacements are dominated by subsidence. Based on GPS results, the affected area of displacements up to end of August 2006 is contained to about 1 km around the extrusion centre. Starting from the third campaign, more GPS stations were observed.

Within this centimeter per day of displacement, will lead us to meters level of displacement in year time period (see table 1). Generaly linier trend can be seen after several month from eruption up to a year time on the series of vertical displacement component on several GPS points investigation (figure 3).

GPS continuous that was set up in RW02 and RW01 between September 2006 and early 2007 give daily rate of vertical displacement or subsidence reached about 3.8 cm/day and 1.8 cm/day. The results also show that about 7-8 months after the first mud extrusion, the subsidence around the main vent area exhibits a linear trend. The horizontal displacements of those two continuous stations are about 1.0 cm/day and 0.6 cm/day (Abidin, 2008).

Table 1 Subsidence result for 1 year after eruption, and rates in first four and next four month

Spatial constrain	Point	Subsidence in first 1 year (m)	Rate of subsidence in first four month (cm/day)	Rate of subsidence in next four month (cm/day)
Inner caldera	PBRK	-4.060	-0.011	-0.014
	RIG1	-8.716	-0.023	-0.031
	TOLL	-3.638	-0.010	-0.013
	SIRN	-3.544	-0.009	-0.013
	JTRJ	-1.732	-0.005	-0.006
	PSKO	-1.564	-0.004	-0.006
	INSR	-6.875	-0.017	-0.025
	RW01	-6.145	-0.018	-0.022
	RW02	-10.958	-0.024	-0.038
	JBSIR	-6.868	-0.018	-0.025
Rim of caldera	PRTL	-0.723	-0.001	-0.003
	SWH	-0.171	0.000	-0.001
	GLAG	-0.341	-0.001	-0.001
	SNGN	-0.542	-0.001	-0.002
	BND2	-1.995	-0.003	-0.009
	GMPL	-0.310	0.000	-0.002
	JBSR	-0.696	-0.001	-0.003
	RMKN	-0.576	-0.001	-0.002
	PJKN	-0.126	0.000	-0.001
Outer of Caldera	KLDN	-0.149	0.000	0.000
	1210	-0.060	0.000	0.000
	KCMT	-0.050	0.000	0.000
	JBPR	-0.090	0.000	0.000
	GPOL	-0.100	0.000	0.000
	ORF	-0.075	0.000	0.000
	UUU1	-0.075	0.000	0.000
	BMT2	-0.125	0.000	-0.001
	BMT4	-0.069	0.000	0.000
	CNDI	-0.250	0.000	-0.001

When we expressed the ground displacement around LUSI mud volcano, we divided the spatialy displacement into ’spatial constrain’ of inner caldera, rim caldera and outer caldera (see table1). The reason that we found generally different characteristic of displacement among those spatial constrain. We conclude that displacement around inner caldera is associate with caldera formation processes and expressed by rapid subsidence characteristic (andreas *et.al*, 2009, 2009a, 2010). Meanwhile the rim and outer caldera has normal caracteristic of subsidence which are most probably associate with the effects of mud loading, ground relaxation due to mud outflow, etc.

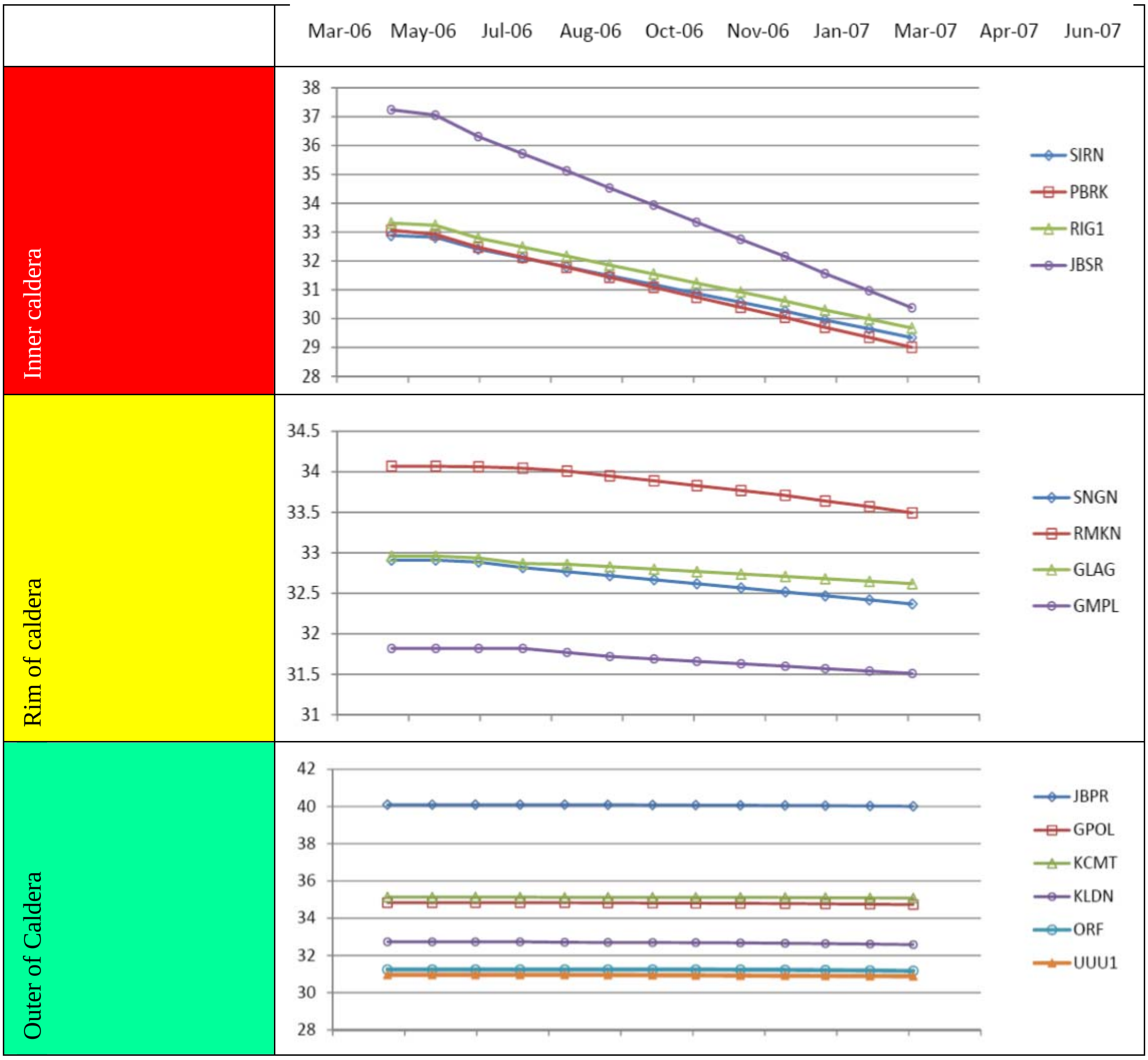

Figure 3 Graphic trend after several month from eruption up to a year time, on the series of vertical displacement component (in meter) on several GPS points investigation in LUSI area.

A very much interesting to see from the first year ground displacement observation result, the pattern of horizontal displacement showed concentrate outlook toward the center of subsidence, meanwhile the vertical displacement given the model of cone subsidence (figure 4a, 4b). This two information will shown good fact on explaining caldera formation processes that happening in LUSI mud volcano. Together with other informations such as field surface representation of displacement, occurred buble plotting, microseismic, etc. we can be sure that no doubt caldera formation is being develop in LUSI mud volcano (figure 4c).

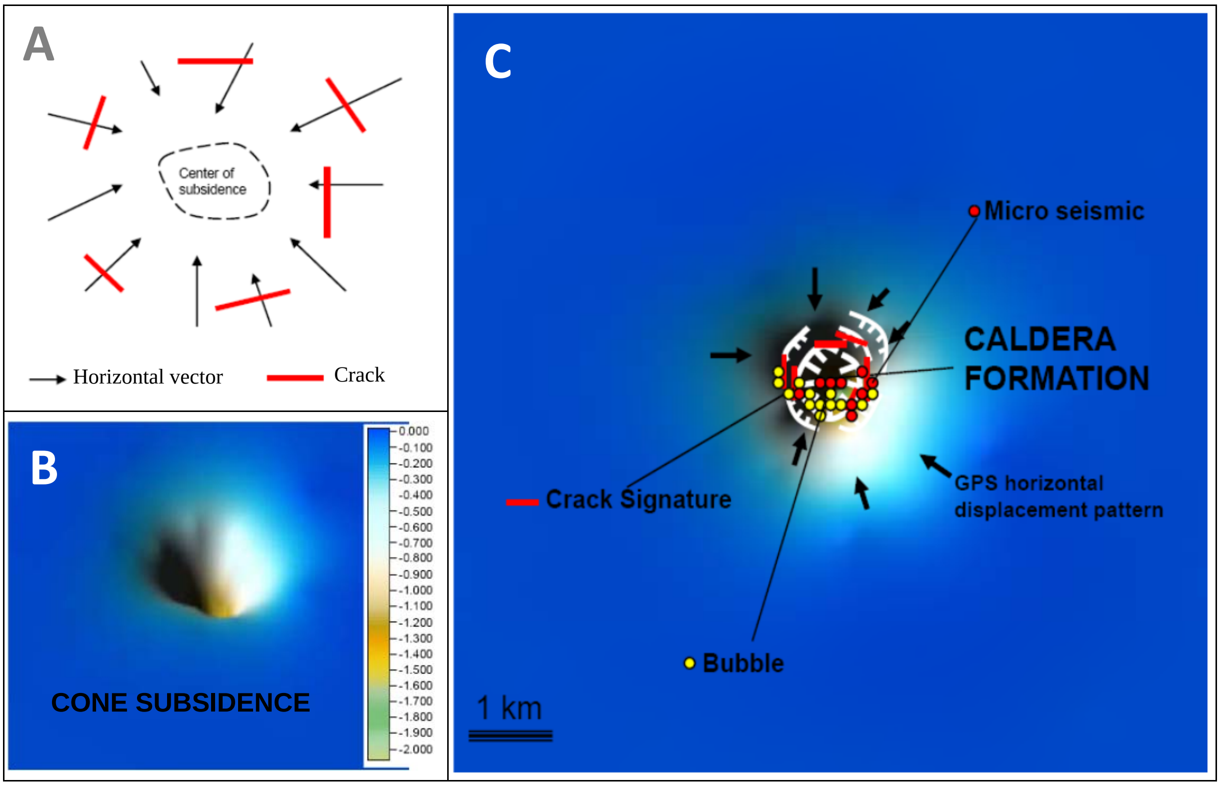

Figure. 4 (a) GPS model derived horizontal displacements (b) the vertical displacement given the model of cone subsidence, (c) Illustration of caldera formation processes on recently birth LUSI Mud Volcano

3.2 After four years result

From the complete result of the whole GPS surveys (more than four years), unfortunately we were not getting the complete time series of ground displacement in every points of observations for the whole those time spand of observation because of the change in mud coverage area that given the consequences to the number of observed GPS stations. In this case the places and the numbers of observation were becoming different from survey to survey (the observed stations could not always be the same). But, fortunately we still can made a model of the ground displacement based on interpolation and extrapolation.

So what happen after four years of the erruption turn out that the ground displacement has slowering at rates. Its not 2-4 cm/day anymore but only several centimeter up to desimeter in a years time (table 2). A linier trend were replaced by exponential decay instead (figure 4).

Table 2 Subsidence result after 4 year from erruption, and rates in 1,2,3,4 year from erruption

Spatial constrain	Point	Subsidence after 4 year (m)	Rate of subsidence year 1 (m/year)	Rate of subsidence year 2 (m/year)	Rate of subsidence year 3 (m/year)	Rate of subsidence year 4 (m/year)
Inner Caldera	RIG1	Un-identify due to chaotic grabben processes on phase of caldera formation processes	-8.716	Un-identify due to chaotic grabben processes on phase of caldera formation processes		
	JBSR		-6.868			
	SIRN		-3.544			
	TOLL		-3.638			
	PBRK		-4.060			
	PSKO		-1.564			
	PS02		-1.564			
	BND2		-1.995			
	JTRJ		-1.732			
Rim of Caldera	JBSR	-1.25	-0.696	-0.277	-0.184	-0.093
	RMKN	-0.95	-0.576	-0.207	-0.098	-0.068
	SNGN	-0.99	-0.542	-0.246	-0.133	-0.068
	PRTL	-1.15	-0.723	-0.240	-0.130	-0.060
	GLAG	-0.68	-0.341	-0.179	-0.106	-0.054
	BPN184	-0.58	-0.322	-0.132	-0.085	-0.044
Outer of Caldera	1210	-0.13	-0.060	-0.030	-0.020	-0.020
	PJKN	-0.20	-0.126	-0.030	-0.020	-0.020
	GMPL	-0.49	-0.310	-0.090	-0.060	-0.030
	SWH1	-0.30	-0.171	-0.070	-0.040	-0.020
	JBPR	-0.17	-0.090	-0.030	-0.030	-0.020
	PGN1	-0.16	-0.090	-0.009	-0.039	-0.020
	BMT2	-0.24	-0.125	-0.086	-0.011	-0.021
	BT16	-0.14	-0.060	-0.040	-0.027	-0.010
	BMT4	-0.15	-0.069	-0.044	-0.024	-0.012
	KCMT	-0.11	-0.050	-0.028	-0.018	-0.009
	CNDI	-0.56	-0.250	-0.142	-0.117	-0.056
	KLDN	-0.22	-0.149	-0.041	-0.018	-0.014
	GPOL	-0.16	-0.105	-0.040	-0.010	-0.008
	BM08	-0.14	-0.080	-0.045	-0.010	-0.008
	ORFF	-0.11	-0.075	-0.008	-0.020	-0.007
	UUU1	-0.14	-0.075	-0.061	0.002	-0.007
	KPER	-0.11	-0.050	-0.042	-0.010	-0.005
	LAJK	-0.12	-0.030	-0.030	-0.053	-0.010
	10EE	0.00	0.000	0.000	0.000	0.000

Note that ground displacements (e.g. subsidence) around inner Caldera were un-identify after a year of eruption due to more likely chaotic grabben processes as part of caldera formation processes, plus mud coverage along with its loading efect has made observing or even extrapolating of ground displacements were nearly impossible. In this case, we left blank information on such ground displacement processes around inner caldera after first year of eruption (table2, figure 4). This first year asumption based on fact we fortunately still can observed displacement in some GPS points at inner caldera in this period (tabel1).

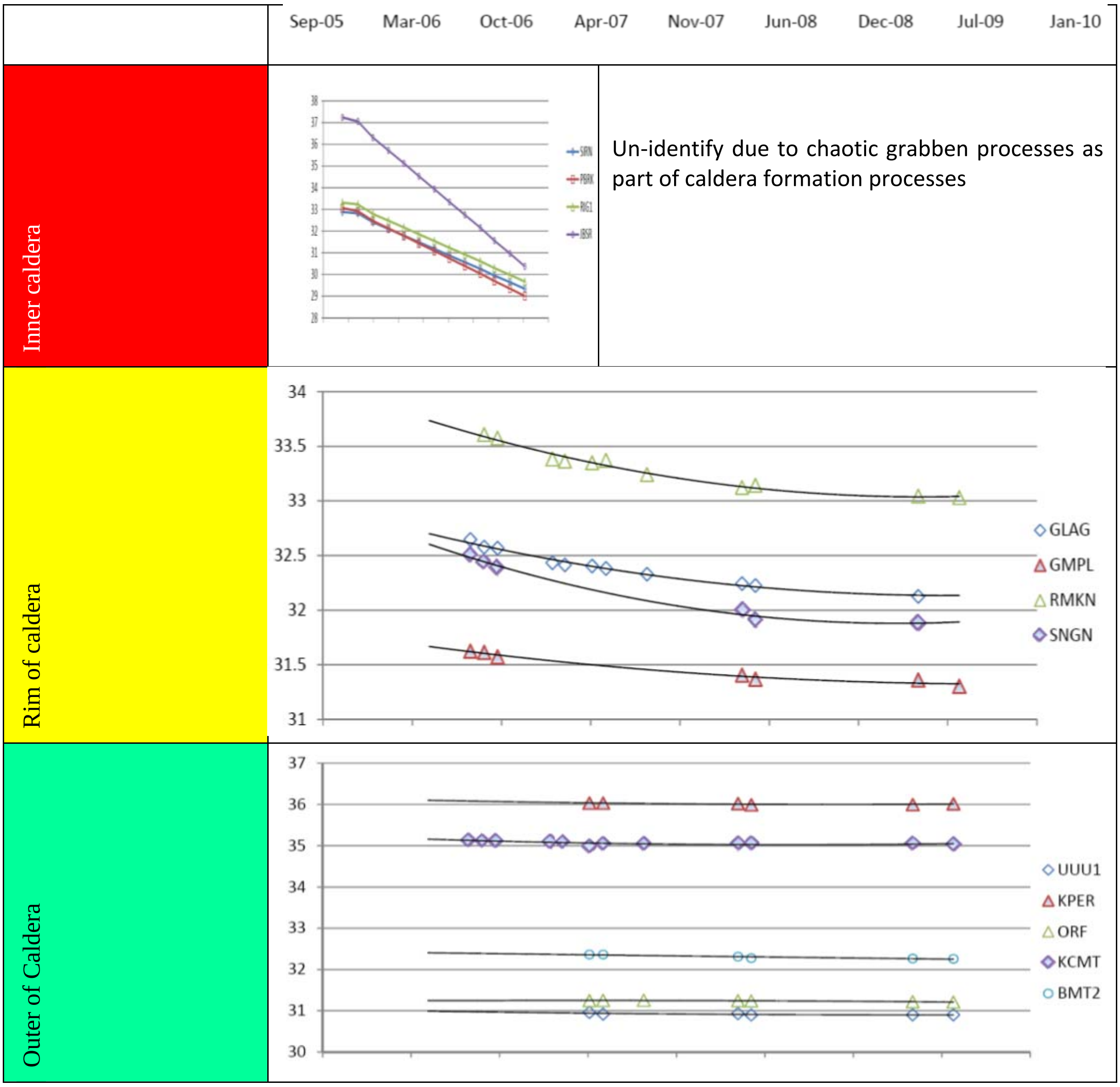

Figure 4 Graphic trend after around four year time from erruption, on the series of vertical displacement component on several GPS points investigation in LUSI Mud Volcano area.

3.3 Sign of LUSI ending eruption?

As mentioned previously, that the effects of mud loading, collapse of the overburden due to the removal of mud from the subsurface (eruption) and, settlement caused by surface works (e.g. construction of dykes), etc., leading to ground displacements around LUSI Mud volcano. If the ground displacement decreasing in rates, it can be mean that factors derived them might timely dissapear (e.g. ending of eruption). If somehow that the ground displacement stopped, that mean that factors derived them might no longer exist (e.g. the mud eruption ended).

Fact has shown that after four years of the LUSI erruption turn out that the ground displacement has slowering at rates. Its not 2-4 cm/day anymore but only several centimeter up to desimeter in a years time. A linier trend were replaced by exponential decay instead. In this cased, this exponential decay might be indicating or signing the ending of LUSI Mud volcano eruption. From the displacement projection result, after ten year period we will see rate generaly 1-2 cm/years surrounding the eruption area which we can simply conclude that eruption may be ignored, and within twenty years we will see the rates generally less then cm/year which can be state that the eruption generaly ended.

Seeing other research (Davies et.al, 2010) which made prediction of 26 years probabilistic longevity estimate for the LUSI mud volcano eruption, a very much similarity in the eruption time prediction found with our result (~20 years).

3 SUMMARY

GPS observations, both in campaign and continuous mode were conducted to study ground displacement phenomenon that following the birth and development of LUSI mud volcano. The GPS derived displacements from the GPS campaigns showed that the surface displacements in the mud volcano area of Sidoarjo have both horizontal and vertical components.

The first 4 months of mud extrusion showed the rates of displacements (from data compilation and interpolation) are in the order of 0,4 to 2,5 cm/day and increasing on the next 8 to 12 month later into 0,6 to 3,8 cm/day for vertical component surrounding the erruption site. After four years of the erruption turn out that the ground displacement has slowering at rates. Its not 2-4 cm/day anymore but only several centimeter up to desimeter in a years time. A linier trend were replaced by exponential decay.

Since the displacement associate with the eruption, the exponential decay might be indicating or signing the ending of LUSI Mud volcano eruption. From the displacement projection result, after ten years period we can simply conclude that erruption may be ignored, and within twenty years from the first eruption we may state that the eruption is generaly ended.

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BIOGRAPHICAL NOTES

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