Environ Geol
DOI 10.1007/s00254-008-1363-4

ORIGINAL ARTICLE

Subsidence and uplift of Sidoarjo (East Java) due to the eruption of the Lusi mud volcano (2006–present)

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Received: 17 April 2008 / Accepted: 28 April 2008

Abstract Global positioning system (GPS) and satellite-based InSAR (Interferometric Synthetic Aperture Radar) measurements of the subsidence and uplift of a populated area of Sidoarjo, East Java are due to the eruption of the Lusi mud volcano (2006–present). These data are the first direct quantitative measurements of deformation due to the growth of a mud volcano edifice. The GPS data were recorded over periods of a few hours to several months and show that between June 2006 and September 2007, the earth's surface has been subsiding at rates of 0.1–4 cm/day. Maximum rates of subsidence occurred in an area 300–400 m to the northwest of the main mud volcano vent. Horizontal displacements were 0.03–0.9 cm/day and were also towards this area. In general uplifts of up to 0.09 cm/day were recorded in areas outside of the edifice. Changes in elevation measured using satellite imagery (InSAR technique) provide regional datasets of subsidence and uplift. They confirm that during the first year a roughly circular area was undergoing sag-like subsidence centered to the northwest of the main vent and that uplift was occurring 3–4 months after the initiation of the eruption due to the movement Watukosek fault system. Subsidence occurred due to the weight of mud and man-made dams and the collapse of the overburden due to removal of mud from the subsurface. Assuming constant rates of subsidence of 4 cm/day, then in the centre of the edifice there would be up to 44 m of subsidence in 3 years, and up to 16 m in 10 years. The mud volcano is now in a self-organizing state with new fluid conduits forming as a result of the collapse.

Keywords Mud volcano · Sidoarjo · Subsidence · Lusi · Collapse · Caldera

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Introduction

On May 29th 2006 the Lusi mud volcano started to erupt in the subdistrict of Porong, in Sidoarjo, East Java, Indonesia (Davies et al. 2007; Fig. 1). An almost continuous eruption of a mud, water and gas mix has occurred since May 2006 that has caused significant damage to livelihoods, the environment and infrastructure. Major impacts on the wider marine and coastal environment are expected, with knock-on effects for the many thousands of people who depend on local fish and shrimp industry for their living. The mud volcano has flooded and destroyed 10,426 houses, 33 schools, 4 offices, 31 factories, 65 mosques, 2 religious schools, 1 orphanage, and 28 other buildings. Fourteen people have been killed, about 10,000 people have had to be evacuated, and 2,441 people have lost their jobs as a result of the destruction of factories. The 5,397 students, 405 teachers, and 46 staff of the destroyed schools are also affected (Kompas 2007).

Although thousands of mud volcanoes occur on earth in compressional tectonic settings, deltas, and other regions

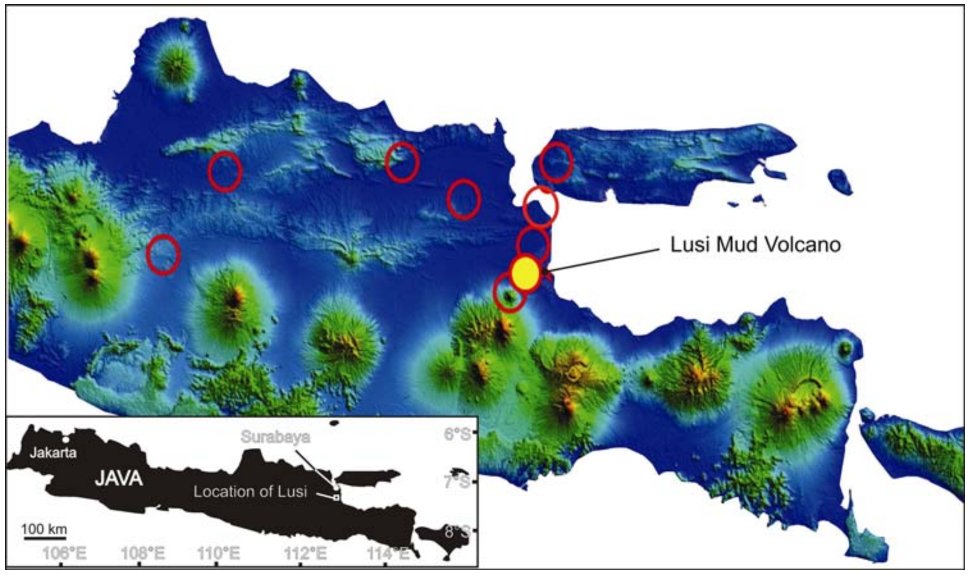


Fig. 1 Topography of East Java with the location of Lusi and other mud volcanoes shown by *red circles*

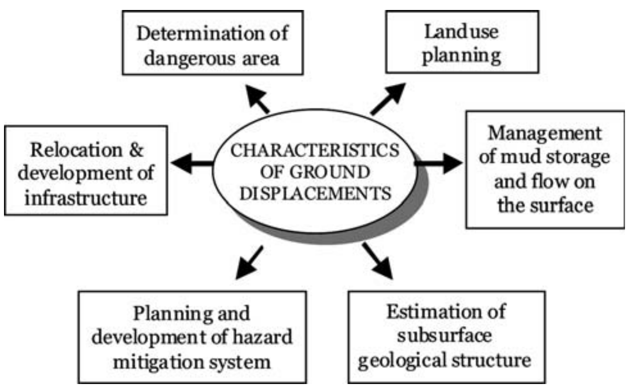


Fig. 2 Diagram showing the significance of ground displacement measurements for the understanding of the effect on the environment and in predicting the subsurface structure

where overpressure has developed in sedimentary rocks (Milkov 2000), the study of mud volcanoes is in its infancy. Recent research where mud volcanoes are analyzed using seismic reflection imagery shows that the eruption of the mud volcano causes the earth's surface to undergo subsidence (Davies and Stewart 2005; Stewart and Davies 2006). This results in the development of sags and sometimes downfaulted calderas (Davies and Stewart 2005; Evans et al. 2007, 2008). However, the birth of a mud volcano has not been witnessed before. Volcanoes have erupted in sparsely populated regions and mud volcanoes generally grow over long periods of time (10^4 to 10^6 years). As a result, there are no direct measurements of the vertical (and potentially horizontal) displacements of the earth's surface due to volcano growth. The rate and duration of the Lusi mud volcano has unusually been high (Davies et al. 2007). The mud volcano also occurred in a heavily populated region and for these reasons the first ever measurements of vertical and horizontal displacements have been recorded, using two independent techniques. This paper describes the measurements, as they are important for the future management of the disaster area (Fig. 2), interprets how and why the surface of the earth's crust is deforming and perhaps most importantly, attempts to predict what the next developmental stages will be.

The Lusi mud volcano

Mud volcano systems are common on the island of Java and particularly in eastern Java. Lusi erupted in the East Java basin, which is an inverted extensional basin (Matthews and Bransden 1995) that comprises of a series of east–west striking half-graben that were active in extension during the Paleogene and reactivated in compression during the Early Miocene to Recent. Oligo-Miocene Kujung Formation limestones within one of these east–west trending anticlines was targeted by the Banjar Panji-1 exploration well.

Photographs (Fig. 3) and satellite photographs (Figs. 4, 5a, b, c) show the main features of the mud volcano. Sequential satellite photos taken every few months show the lateral growth of the edifice from 3.6 km^2 in August 2006 to 6.9 km^2 in May 2007 (Fig. 4). As the perimeter of the mud edifice is now protected by man-made dykes, the present extent at the time of writing (April 2008) was still about 7 km^2. Based upon an estimated density of the mud of 1.5 gcc^{-1} and a volume of mud to 0.012 km^3 18,000,000 metric tonnes of mud have erupted. The eruption started from several vents aligned approximately with the trend of the northeast-southwest striking Watukosek

Fig. 3 Selection of photographs of the Lusi mud volcano mainly from May 2006 to September 2007 showing the environmental impact and main features. **a** Main vent photographed within a few months of eruption initiation. **b** Bubble number 76 erupting during February 2008 outside area of edifice near a factory. **c** Flooded factories. **d** Regions where mud has settled to leave extensive regions of erupted water. **e** Flooded houses. **f** Regions where the mud had dried and cracked. **g** Flooded railway on the western side of Lusi. **h** Initial flooding of the toll road, which runs across the centre of the edifice. **i** Abandoned village

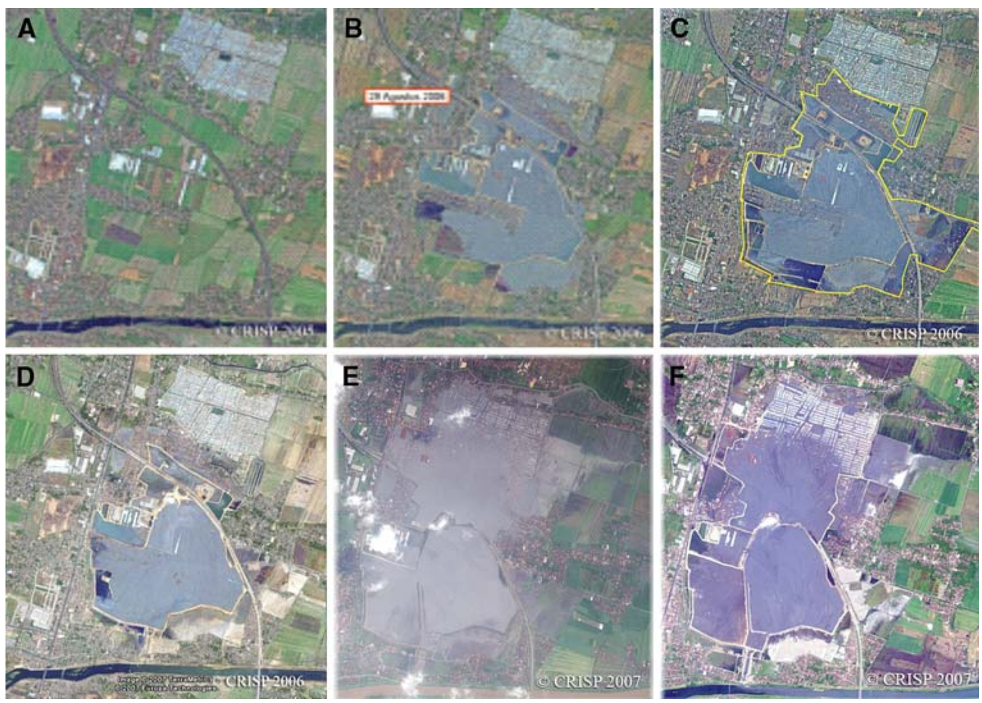


Fig. 4 Selection of satellite photographs from October 2005 to May 2007 showing the progressive growth of the Lusi edifice. **a** 6th October 2005. **b** 29th August 2006. **c** 17th September 2006. **d** 20th October 2006. **e** 22nd April 2007. **f** 11th May 2007. Field of view is approximately 3.5 km wide. Satellite images are published with the permission of CRISP. Ikonos Satellite Image©CRISP, NUS (2007)

fault system (Mazzini et al. 2007). However, most were short lived and there is now one main central vent [termed the 'main vent' in this study (Figs. 3, 5a–c)].

Two mechanisms have been proposed as trigger mechanisms for the volcano, the Yogyakarta earthquake which occurred on the 27th May 2006 and the drilling of a gas exploration well 150 m from where the main eruptive vent is today. Manga (2007) showed that the earthquake was either not significant enough in magnitude or too far away from Sidoarjo to have caused the eruption. Davies et al. (2007) proposed that it was triggered by the drilling. Mazzini et al. (2007) proposed that the earthquake reactivated the northeast–southwest trending Watukosek fault and caused the volcano to form.

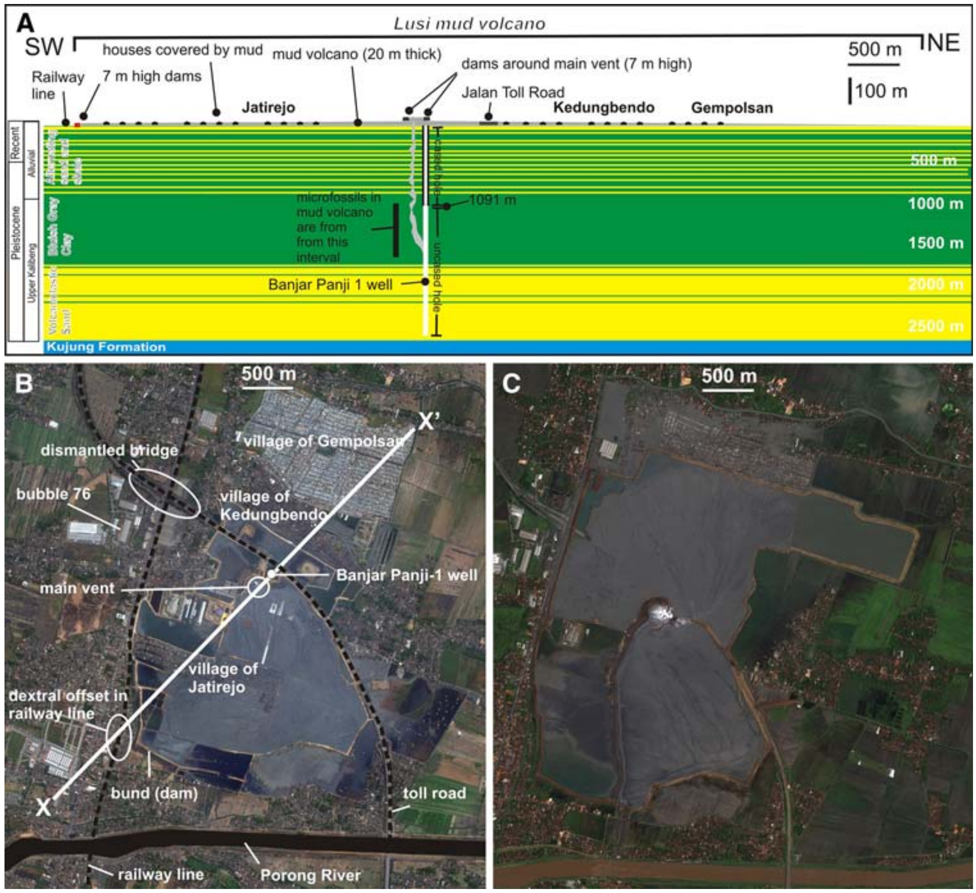


Fig. 5 **a** Simplified SW–NE cross section through the Lusi mud volcano and subsurface geology. *Thin grey lens* mud volcano. *Black boxes* houses. *Yellow* sandstone. *Green* mudstone. *Blue* limestone. **b** Satellite photograph from October 2006 with features that are mentioned in the text labeled. **c** Satellite photograph from January 2008. Satellite images are published with the permission of CRISP. Ikonos Satellite Image©CRISP, NUS (2007/2008)

Banjar Panji-1 was a gas exploration well that was targeting gas within Oligo-Miocene age Kujung Formation carbonates within the East Java Basin. Mazzini et al. (2007) reports that the well drilled from shallow to deep: (1) alluvial sediments (2) Pleistocene alternating sandstone and shale of the Pucangan Formation, (up to 900 m depth), (3) Pleistocene bluish gray clay of the Upper Kalibeng Formation, to 1,871 m depth and (4) volcaniclastic sand at least 962 m in thickness (Fig. 5a). The nearest other exploration well is the Porong-1 well, which was drilled 6.5 km to the northeast from Sidoarjo and seismic correlations from this well to Banjar Panji-1 show that beneath these sediments is the Kujung Formation carbonates (Fig. 5a). Some of the fossils retrieved from the erupting mud are age-diagnostic, with first or last downhole appearances within the Plio-Pleistocene and Pleistocene, which at this locality occur over a depth range of 1,219–1,828 m (Fig. 5a).

Methodology

There were two strategies for measuring horizontal and vertical displacements using GPS devices: (1) short-term measurements (5–7 h) from numerous stations, and (2) continuous measurements made from a small number of individual stations over specific time periods. InSAR (Interferometric Synthetic Aperture Radar) data (Massonnet and Feigl 1998) provided a greater spatial coverage of subsidence and uplift information and also allowed comparisons with the GPS results. In addition, observations of deformation of buildings, roads and railway lines were collected.

Short-term measurement campaigns

These surveys were conducted during campaigns that lasted 3–7 days between June 2006 and September 2007 using dual-frequency geodetic type receivers, with an observation session length of about 5–7 h. Because the area of the mud coverage has increased through time and stations have had to be abandoned, the number of stations has changed from one survey to another and the area covered by the GPS campaigns has increased. Campaigns 1–3 were localized around the main vent, but campaigns 4–10 covered a larger area. The coordinates of GPS stations were measured relative to a reference station, which has accurately known coordinates and is in a stable area that is not

Table 1 Details of short-term measurement campaigns 1–10, including the number of stations used and location of the stations relative to the main vent

Campaign number	Time of survey	Number of stations	Distance from the main vent (km)
1	29 June to 2 July 2006	14	0.5–1
2	23–25 July 2006	12	0.5–1
3	26–29 August 2006	19	3–4
4	17–20 September 2006	17	3–4
5	12–15 October 2006	9	3–4
6	4–11 February 2007	9	3–4
7	10–12 March 2007	8	3–4
8	5–11 May 2007	23	3–4
9	9–13 June 2007	29	3–10
10	16–20 September 2007	31	3–10

affected by ground deformation. Vertical and horizontal displacements of a GPS station are derived using its 3D coordinates obtained from two consecutive GPS surveys. To have consistent coordinates for all stations, only one reference station was used in each campaign. Ten GPS campaigns were conducted in this way (Table 1). The location of GPS stations was decided by considering (1) ease of operation given field conditions, (2) minimal sky obstruction for GPS signals and (3) the likelihood that subsidence would be recorded.

Processing of GPS survey data was conducted using GPS processing software Bernese 4.2 (Beutler et al. 2001). Precise orbital information of GPS satellites was used in all data processing. In general, standard deviations of the estimated coordinates are only a few millimeters for horizontal and vertical movements.

Continuous measurement

From 22nd September 2006 continuous GPS monitoring using between five and ten stations with various observation lengths was carried out. The results from two representative stations (RW01 and RW02) were reported. Station RW01 was monitored between 22nd September and 23rd January 2007 and station RW02 was monitored between 6th November and 9th December 2006. Originally, these two continuous measurements were conducted to provide ground deformation information for supporting the operational safety of two relief wells. Therefore, the stations were located close to relief well sites. At the same time, these locations were selected on the basis that they were unlikely to be flooded by the erupting mud–water mix and were close enough to the main vent to be able to record measurable magnitudes of subsidence.

InSAR measurements

The InSAR technique has been applied to the Sidoarjo area using ALOS (the Advanced Land Observing Satellite) and PALSAR data. Interferograms are generated using two satellite images taken at different times. The wavelength for the InSAR measurement used was about 23.6 cm. To estimate the rate of subsidence per day, the number of coloured fringes on the interferogram are counted and multiplied by the wavelength and then divided by the time period between the two images. The sequence of colour fringes can be used to determine whether uplift or subsidence has taken place.

Results

Short-term measurements

The GPS derived displacements from the campaigns 1–3, conducted in June, July and August 2006 (Table 2) shows that the land surface has undergone horizontal and vertical displacements (Fig. 6a, b). It is also apparent that in the first three months of mud extrusion (Fig. 6a, b), the rate of displacements increased with time (Table 2). The rates of horizontal and vertical displacement can be up to 2 and 4 cm/day, respectively. Vertical displacements are much higher than horizontal displacements. The area that had started to subside within 3 months of the initiation of the Lusi edifice, had a radius of approximately 1 km around the main vent (green yellow and orange area in Fig. 6a, b).

The results obtained from the ten campaigns (Table 2), show that ground displacements around the mud volcano area vary in terms of rate and direction. However in general, during the first year the horizontal displacements are directed towards an area about 300–400 m northwest of the main vent of mud extrusion the location of the Banjar Panji-1 well (dashed circle in Fig. 6a, b). The results show that during the first 3 months of edifice growth the land surface within a 1 km radius of the main vent underwent rapid rates of subsidence, which then slowed from the middle of October 2006 (Table 2) (cf. Figs. 6a, b; 7a–d). Most recently, during February–March 2008, the subsidence rate adjacent to the main vent has shown evidence for sporadic increases in subsidence rate, up to 6–20 cm/day, and once reached 1 and 3 m over a 12-h period (Joyopranoto, personal communication).

Although subsidence is dominant there is also evidence for uplift. The uplift of some GPS stations was first detected between the 3rd and 4th GPS campaigns on 26–29th August 2006 and 17–20th September 2006 (Fig. 7a, c).

Table 2 Summary of GPS-derived rates of vertical and horizontal displacements

Campaign number	Period	Vertical displacement	Horizontal displacement
1–2	June–July 2006	Rate < 1.1 cm/day; subsidence (all stations)	Rate < 0.3 cm/day; directions: all to northwest of the main vent
2–3	July–August 2006	Rate < 3.6 cm/day; subsidence (all stations)	Rate < 0.9 cm/day; directions: all to northwest of the main vent
3–4	August–September 2006	Rate < 2.1 cm/day; subsidence and uplift	Rate < 0.7 cm/day; directions: mostly to northwest of the main vent
4–5	September–October 2006	Rate < 2.4 cm/day; mostly subsidence	Rate < 0.9 cm/day; directions: mostly to northwest of the main vent
5–6	October 2006 to February 2007	Rate < 0.3 cm/day; subsidence (all stations)	Rate < 0.3 cm/day; directions: all to northwest of the main vent
6–7	February–March 2007	Rate < 0.3 cm/day; mostly subsidence	Rate < 0.3 cm/day; directions: some to northwest of the main vent
7–8	March–May 2007	Rate < 0.2 cm/day; subsidence and uplift	Rate < 0.1 cm/day; directions: some to northwest of the main vent
8–9	May–June 2007	Rate < 0.2 cm/day; subsidence and uplift	Rate < 0.1 cm/day; directions: no clear pattern
9–10	June–September 2007	Rate < 0.1 cm/day; subsidence and uplift	Rate < 0.03 cm/day; directions: no clear pattern

Because vertical and horizontal displacements of a GPS station are derived using its 3D coordinates obtained from two consecutive GPS surveys, two consecutive campaigns were required to calculate rates of vertical and horizontal displacement

Continuous monitoring

Representative data from the two continuous monitoring GPS stations, RW01 and RW02 are shown, which are about 750 m from the main vent (Fig. 8a). Station RW01 was operated between 22nd September 2006 and 23rd January 2007 and station RW02 was operated between 6th November 2006 and 9th December 2006. The operation of both stations was terminated because the sites became unsafe due to the continued eruption of mud. At the time of writing mud covers both locations. The observed subsidence rate was 1.8 cm/day at RW01 and was 3.8 cm/day station at RW002 (Fig. 8b, c, respectively). The horizontal displacements of the two stations are about 0.6 cm/day (RW01) and 1.0 cm/day (RW02), with the directions of horizontal displacement again being towards a region 300–400 m northwest of the main vent (circled region in Fig. 8a). The results also show that about 7–8 months after the first mud extrusion, the rate of subsidence around the main vent area was linear with no evidence of increasing or slowing down. At these rates this part of the mud volcano should have subsided between 13.1 and 27.66 m in the 2 years since the eruption started.

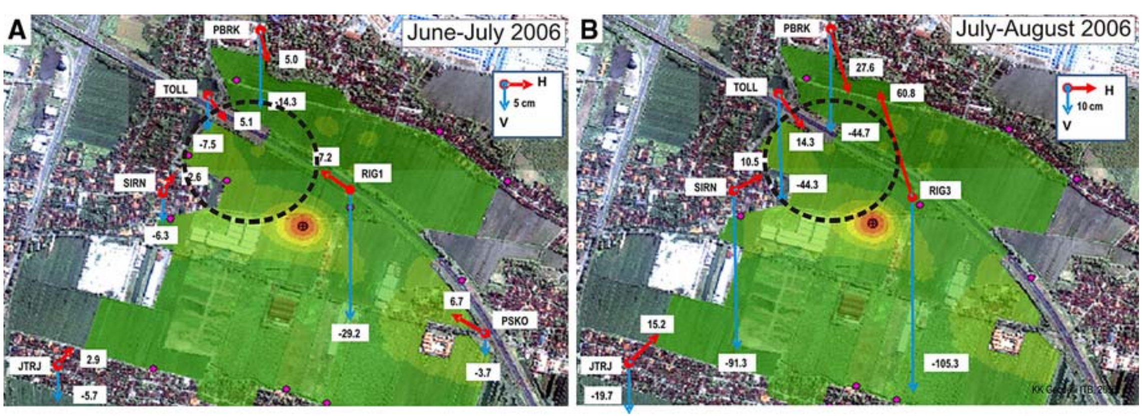


Fig. 6 The first short-term measurement campaigns (campaigns 1–3) after initiation of the eruption. The area covered by these campaigns was localized around the main vent (*orange bulls eye*). **a**, **b** Horizontal and vertical displacements between June and July 2006 and July and August 2006. *White boxes* displacements in centimeters, - = subsidence. *V* vertical displacement, *H* horizontal displacement. *Length of arrows* in each case is proportion to the displacement

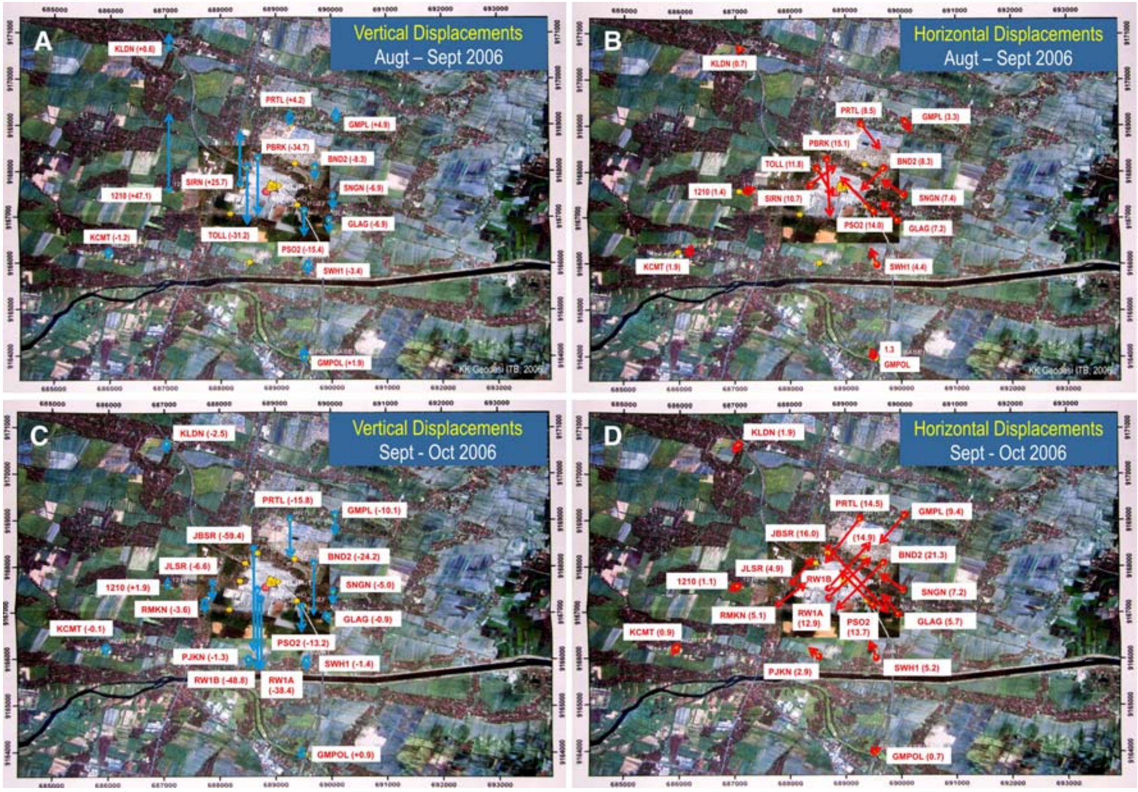


Fig. 7 Representative results from campaigns 4–10. **a**–**d** Vertical and horizontal displacements during (August and September and September and October) covering a much larger area. *White boxes* displacements in centimeters, + uplift, − subsidence. *Blue arrows* vertical displacement. *Red arrows* direction of horizontal displacement. *Length of arrows* in each case is proportion to the displacement. GPS locations were given names (e.g. Toll, Rig1)

InSAR data

A reference satellite image taken before the eruption started on 19th May 2006 was used to generate interferograms for periods between this date and subsequent months. Representative interferograms were shown from July 2006 to February 2007 (Fig. 9a–f). During this time an ovoid-shaped sag formed at the location of the mud volcano edifice, at an average subsidence rate of between 1 and 4 cm/day (Fig. 9b–f). By August 2006 (Fig. 9b) there is also evidence for uplift to the northeast of the ovoid-shaped sag. The uplifted region has an abrupt southern margin that lines up with the Watukosek fault system (Fig. 9c, d). This area of uplift is almost indiscernible in the July 2006 interferogram (Fig. 9a). A second ovoid depression forms to the northwest of the Lusi edifice (Fig. 9b–f). It is spatially coincident with the Wunut gas field. The interferograms do not resolve subsidence in the central part of the edifice very well and therefore areas of enhanced subsidence identified using the GPS technique cannot be

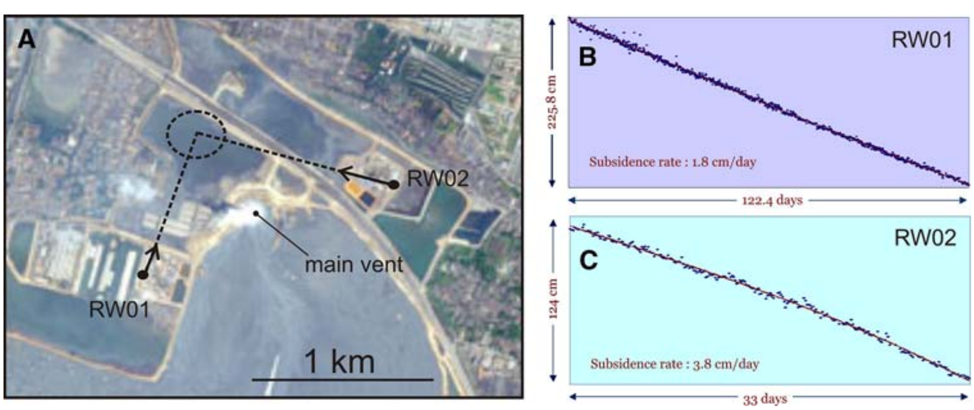
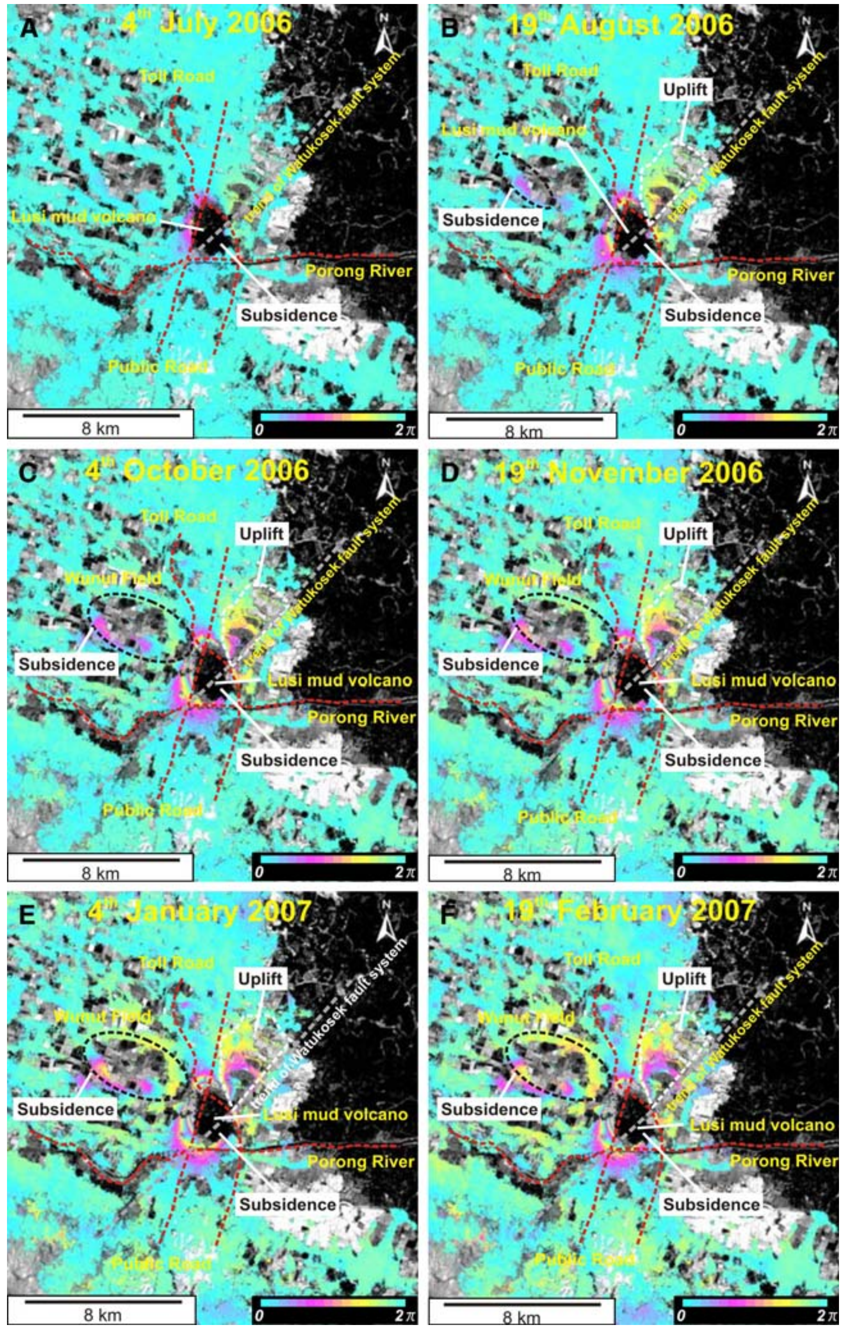


Fig. 8 **a** Satellite photograph showing the location of RW01 and RW02 and horizontal displacements directed towards the northwest of the main vent. **b** Subsidence from 22nd September 2006 to 23rd January 2007 for location RW01. **c** Subsidence from 6th November to 9th December 2007 for location RW02. Satellite image is published with the permission of CRISP. Ikonos Satellite Image©CRISP, NUS (2007)

Fig. 9 A series of InSAR interferograms for specific months after the eruption started using 19th May 2006 as the reference satellite image, which was taken before the eruption, began. The location of the toll road, railway line and the Porong River are indicated with *red-dashed lines* so that comparisons can be made with satellite images (Figs. 4, 5). Multiply the number of fringes by 23.6 cm (the wavelength) to estimate the amount of subsidence and uplift. Colour fringes *purple–yellow–blue* denotes subsidence; Colour fringes *yellow–purple–blue* denotes uplift. The InSAR-estimated maximum cumulative subsidence from 19th May 2006 to 19th February 2007 is about 4 m



independently verified. These movements are summarized by the interferogram generated between Februrary 2006 and May 2007 (Fig. 10).

Other surface evidence for displacement

About 4 months after the first mud extrusion, the ground displacements had caused cracks to form in the walls and floors of houses 1–2 km north and east of the main vent. A 71 cm diameter underground gas pipeline exploded on November 22th 2006 and killed 13 people. The pipeline is 2 m under the surface and where the explosion occurred there is a man-made dam that is about 7–8 m high. The explosion was within the area where the highest rates of subsidence have been recorded (Fig. 9a). On 27th September 2006, 4 months after the initiation of the eruption, a dextral movement of north–south orientated railroad on the western side of the mud extrusion was noticed (Fig. 11). This shift was along of the trend of the Watukosek fault system. The ground displacements also affected a concrete two-lane toll bridge in the area. Because of the cracking the bridge was dismantled in the first week of January 2007.

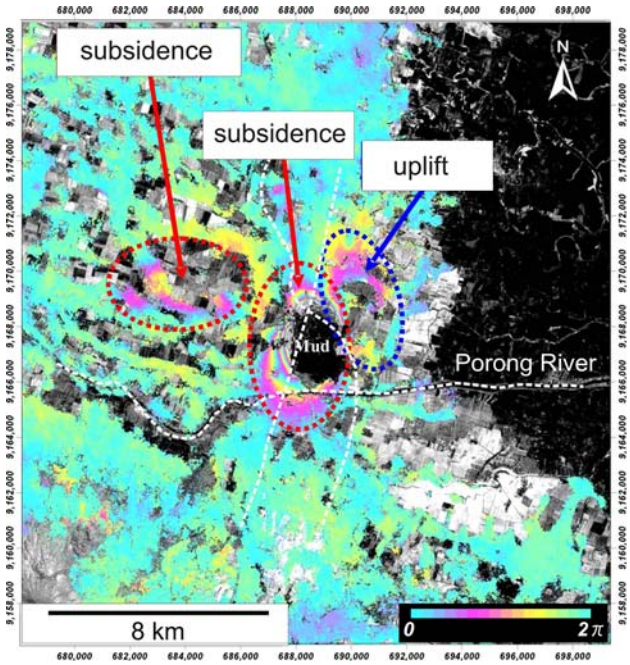


Fig. 10 A summary interferogram for 19th February 2007 with the reference satellite image again from 19th May 2006 before the eruption had started. The location of the toll road, railway line and the Porong River are indicated with *white dashed lines* so that comparisons can be made with satellite images (Figs. 4, 5). Multiply the number of fringes by 23.6 cm (the wavelength) to estimate the total amount of subsidence and uplift during this period. Colour fringes *purple–yellow–blue* denotes subsidence; colour fringes *yellow–purple–blue* denotes uplift

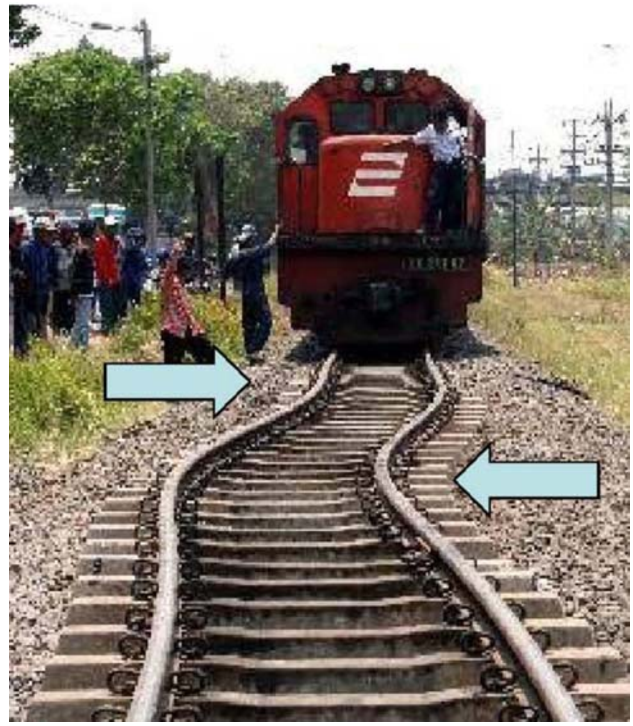


Fig. 11 Photograph of the railway line on the western margin of the Lusi edifice, showing evidence for dextral offset. Photograph taken on 27th September 2006, 4 months after the eruption started. Location of photograph shown on Fig. 5b

Interpretation

Subsidence, uplift and lateral displacement

Vertical displacements in and around the Lusi mud volcano area are mainly driven by: (1) mud loading, (2) collapse of the overburden due to the removal of mud from the subsurface, (3) land settlement caused by surface works (e.g. construction of dykes) and (4) displacements on the reactivated Watukosek fault system) in the area. There could be several explanations for why the maximum rate of subsidence was 300–400 m to the northeast of the main vent during June 2006 to September 2007. It probably indicates that the plumbing system does not comprise a straight, vertical conduit feeding mud from approximately 1,219 to 1,828 m depth to the surface vent. Instead there may have been more erosion of mud by the feeder system in a region northwest of the main vent, at least during the first year of the eruption. It is plausible that the failure of the casing point at or below 1,091 m, (Davies et al. 2007) occurred in the northwestern sector of the wellbore. Alternatively, fractures were concentrated northwest of the wellbore for other reasons.

The uplift to northeast of Lusi has an abrupt southeast margin, which aligns with the Watukosek fault system and occurred during August–October 2006. The photograph of the dextral offset of the railway line was taken in September 2006 (Fig. 11). Therefore, the Watukosek fault system is interpreted to have been reactivated during these months and caused localized uplift. Movement of the Watukosek fault system clearly occurred post July 2006. These two pieces of evidence provide the strongest evidence yet that the Watukosek fault system was not reactivated during the Yogyakarta earthquake.

To the northwest of the edifice a second ovoid depression formed. It is clearly discernable from August 2006 onwards. The sag is coincident with the Wunut gas field and is interpreted to be the result of depletion of the field and subsidence of the overburden. It is interpreted to have no relationship with the Lusi edifice.

The small magnitudes of lateral displacement are more problematic to explain. The occurrence of normal faults downthrown towards the region undergoing the maximum rates of subsidence or towards the main vent could account for lateral displacement (Fig. 12). As constant rates of subsidence have been measured, these normal faults must be minor features.

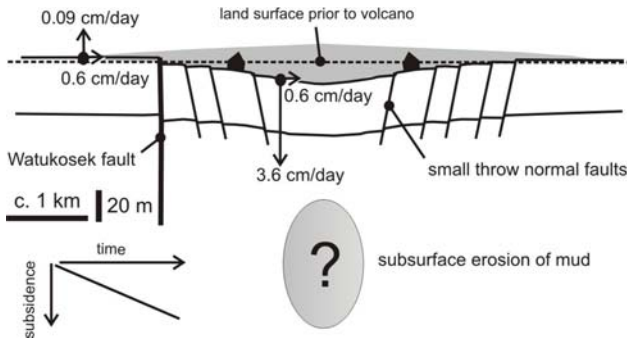


Fig. 12 Explanation for horizontal and vertical displacement. Lateral displacement is caused by small extensional faults. Vertical displacement caused by flexure of the surface and the combined effect of numerous small extension faults. Subsidence curves show continuous subsidence rates

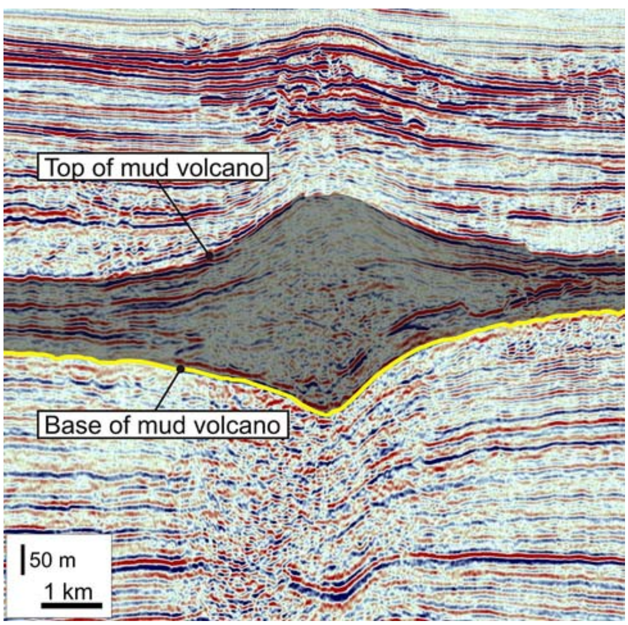


Fig. 13 Seismic cross section through a mud volcano from the South Caspian Sea. The mud volcano forms a biconic geometry, with downward flexure of the earth's surface caused by subsidence. After Stewart and Davies (2006)

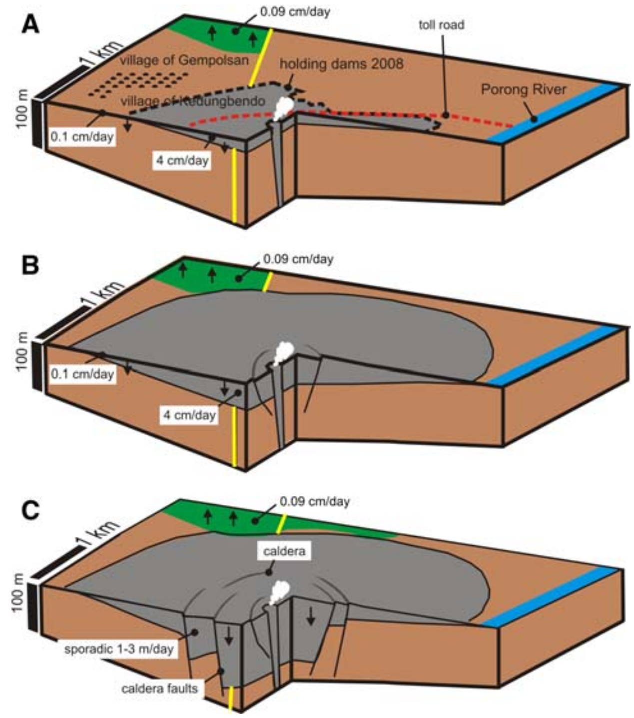


Fig. 14 Schemmatic diagram showing present and predicted subsidence and uplift of the land surface in Sidoarjo. Erupted mud and area of subsidence *grey area*. Uplifted areas *green*. Watukosek fault system *yellow line*. **a** Situation during 2006 and 2007, with subsidence of 0.1–4.0 cm/day. Reactivated Watukosek fault system causes green uplifted region to northeast of Lusi. The mud volcano is confined by holding dams. Sag-like subsidence is dominant, but there is also uplift due to reactivation of the Watukosek fault system. **b** 2008–2010 Expansion of the mud volcano and the initiation of caldera faults. **c** 2010 onwards, caldera faults important and significant subsidence of the central part of the mud volcano

Future development

Insights through comparison with other mud volcanoes

Based upon how other mud volcanoes develop, data presented in this paper can be used to predict the future development of Lusi. Other fossil mud volcanoes typically form a biconic geometry (Fig. 13; Stewart and Davies 2006) with a central caldera (Davies and Stewart 2005). The biconic form probably develops as a result of subsidence of the land or seafloor, which results in a depression that is filled with erupted sediment. The subsidence slows and then the upper half of the biocone forms as a result of continued lateral and vertical growth of the volcanic edifice. A caldera can form central or offset from the middle of the depression (Davies and Stewart 2005; Stewart and Davies 2006). So far Lusi has undergone sag-like subsidence and contemporaneous infill of the resultant depression (Fig. 14a–c). The dramatic increase in the subsidence rate that occurred in February and March 2008 indicates that the central part of the mud volcano is starting to collapse. The development of a caldera around the main vent could account for these dramatic increases in subsidence rate (Fig. 14c). It is expected that the zone of maximum subsidence in the centre of the edifice is where most mud will pond, in turn creating more local subsidence that can be filled with erupting mud. Up to September 2007, the subsidence affects an area up to 8–10 km from the main vent which will increase as the eruption continues (Fig. 14a–c). If a caldera does form rather than lateral expansion of the edifice the volume of mud may be accommodated preferentially within the growing down-faulted caldera region.

Table 3 Estimated subsidence outside the mud edifice and central to the edifice. The subsidence outside mud edifice may spatially vary depends on direction and distance from the main vent

Location	General subsidence rate (cm/day)	Subsidence after 3 years (m)	Subsidence after 10 years (m)
Outside mud edifice (about 3–10 km from the main vent)	0.1	1.1	3.7
Central to edifice	4	44	146

The authors speculate that the Lusi mud volcano is now in a self-organizing state, where eruption of the mud–water mix and erosion of subsurface material causes subsidence and faulting. It has been proposed in other mud volcanoes that new faults develop due to collapse of the central areas and that they provide new pathways for the flow of the mud–water mix (Davies and Stewart 2005). Shallower aquifers could be breached by the new fault systems.

Predicted subsidence of Sidoarjo

The total amount of subsidence of the earth's surface given different assumptions on the longevity of the eruption can be estimated, assuming that the rates measured remain constant (Table 3). Around the margins of the mud coverage area, assuming the general subsidence rate of about 0.1 cm/day, a 3-year life span would mean subsidence of up to 1.1 m, and a 10-year life span would result in subsidence of up to 3.7 m. In the central part of the mud volcano, including the region to the northwest of the main vent, assuming the general subsidence rate of 4 cm/day, a 3-year life span would mean subsidence of up to 44 m, and a 10-year life span would result in subsidence of up to 146 m. Because the subsiding region will be filled with the erupting mud, the subsidence of the land surface may not be obvious. If subsidence occurs without the eruption of mud, then the subsidence of the surface will become more observed.

Conclusions

The eruption of the Lusi mud volcano has triggered vertical and horizontal ground displacements. Subsidence is occurring at steady rates of 0.1 and 4 cm/day resulting in the development of an avoid-shaped sag. If this continues for 3–10 years, it is expected that areas of Sidoarjo in the central part of the edifice will subside between 44 and 146 m. The subsidence in the central parts of the edifice may take place by downfaulting of a caldera. It is proposed that the subsidence occurs due to: (1) mud loading, (2) collapse of the overburden due to the removal of mud from the subsurface and (3) land settlement caused by surface works (e.g. construction of dykes).

Uplift is also occurring and InSAR data indicate that some of this is caused by movement of the Watukosek fault system, which occurred 3–4 months after the eruption started. There is no evidence for the movement of this fault in previous months as a result of reactivation during the Yogyakarta earthquake. The origin of the smaller horizontal displacements is less clear, one simple mechanism is that normal faults are forming and downthrowing towards the mud volcano centre.

Evidence from recent measurements taken in February and March 2008 indicates that subsidence of between 1 and 3 m can take place overnight and this is an indication of faulting and may represent the start of caldera formation. Ultimately, the extent of the deformation associated with the mud volcano will depend upon the life span of the eruption. Given that the eruption has continued for 2 years essentially unabated, future studies should focus on modeling and monitoring the lateral propagation of ground deformation and its environmental impacts. An immediate focus on estimating the length of the eruption is also essential.

Acknowledgments GPS Surveys in Porong Sidoarjo and several site visits were made possible by support provided by the Sidoarjo Mud Mitigation Agency (BPLS) and Lapindo Brantas Inc. The contribution of Muhammad Gamal, Irwan Gumilar, Teguh P. Sidik, Isfahani Buchari and Bramasto A. Wijaya in conducting GPS campaigns is gratefully acknowledged. Soffian Hadi Joyopranoto (BPLS) is thanked for providing up-to-date information about mud volcano. The authors are very grateful to CRISP for permission to publish the satellite images in Figs. 4, 5, 8. RJD thanks Agus Ramdhan for assistance in visiting the Sidoarjo area.

References

Beutler G, Bock H, Brockmann E, Dach R, Fridez P, Gurtner W, Hugentobler U, Ineichen D, Johnson J, Meindl M, Mervant L, Rothacher M, Schaer S, Springer T, Weber R (2001) Bernese GPS software version 4.2. In: Hugentobler U, Schaer S, Fridez P (eds), Astronomical Institute, University of Berne, 515 pp

Davies RJ, Stewart SA (2005) Emplacement of giant mud volcanoes in the South Caspian Basin: three-dimensional seismic reflection imaging of root zones. J Geol Soc 162:1–4

Davies RJ, Swarbrick RE, Evans RJ, Huuse M (2007) Birth of a mud volcano: East Java, 29 May 2006. GSA Today, 17(2)

Evans R, Davies RJ, Stewart SA (2007) Internal structure and eruptive history of a kilometre scale mud volcano system, South Caspian Sea. Basin Res 19:153–163

Evans RJ, Stewart SA, Davies RJ (2008) The structure and formation of mud volcano summit calderas. J Geol Soc Lond 165:1–12

Kompas (2007) Indonesian National Newspaper, Saturday, 26th May 2007, pp 33–40

Manga M (2007) Did an earthquake trigger the May 2006 eruption of the Lusi mud volcano? EOS 88:201

Massonnet D, Feigl KL (1998) Radar interferometry and its application to changes in the earth's surface. Rev Geophys 36:441–500

Matthews SJ, Bransden PJE (1995) Late cretaceous and cenozoic tectono-stratigraphic development of the East Java Sea Basin, Indonesia. Mar Petroleum Geol 12:499–510

Mazzini A, Svensen H, Akhmanov GG, Aloisi G, Planke S, Malthe-Sørenssen A, Istadi B (2007) Triggering and dynamic evolution of LUSI mud volcano, Indonesia. Earth Planet Sci Lett 261:375–388

Milkov AV (2000) Worldwide distribution of submarine mud volcanoes and associated gas hydrates. Mar Geol 167:29–42

Stewart SA, Davies RJ (2006) Structure and emplacement of mud volcano systems in the South Caspian Basin. AAPG Bull 90:771–786