Gravity monitoring of Tatun Volcanic Group activities and inference for underground fluid circulations

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**Abstract**

The Tatun Volcano Group (TVG), located on the northern coast of Taiwan adjacent to the city of Taipei, experiences active hydrothermalism but has no historical record of volcanic eruption. Yet recent studies suggest that TVG is dormant-active rather than extinct. To monitor mass transfers and to gain further understanding of this volcanic area, gravity variations have been recorded continuously since 2012 using a superconducting gravimeter, and once every few months since 2005 using absolute gravimeters. We analyze the continuous gravity time series and propose a model that best explains the gravity variations due to local groundwater redistribution. By correcting these variations, we identify gravity changes as large as 35 \(\mu\)Gal that occurred concomitantly to fluid pressure-induced earthquakes and changes in the gas composition at Dayoukeng, one of TVG’s fumaroles, over 2005–2007. We examine several fluid movements that can match the gravity observations, yet too few additional constraints exist to favor any of them. In particular, no significant ground displacements are observed when these gravity variations occurred. On the other hand, the model of gravity changes due to local groundwater redistribution can be routinely computed and removed from the ongoing time gravity measurements in order to quickly identify any unusual mass transfer occurring beneath TVG.

**1. Introduction**

The Tatun Volcano Group (TVG) covers an area of 400 km\(^2\) in the northern tip of the island of Taiwan adjacent to the metropolis of Taipei (Fig. 1). It consists of more than twenty Quaternary volcanoes and has been experiencing a sustained seismic and hydrothermal activity (Lin et al., 2005; Lee et al., 2008). TVG is generally associated with the Ryukyu volcanic arc to the east, which results from the subduction of the Philippine Sea plate beneath the Eurasian plate (Teng, 1996; Kim et al., 2005). An alternative hypothesis is that TVG resulted from a post-collisional lithospheric extension associated with the collapse of the northern Taiwan mountain belt (Wang et al., 1999). As for the timing of TVG eruptions, rock dating revealed two main periods of volcanic activity, at 2.8–2.5 Ma and 0.8–0.2 Ma (Wang and Chen, 1990; Song et al., 2000). However, Belousov et al. (2010) suggested that magmatic eruptions occurred as recent as 13,000–23,000 years ago and that a late phreatomagmatic eruption happened only 6000 years ago. Despite the fact that there is no record of historical eruptions, Belousov et al. (2010) maintained that the last eruptions are recent enough to consider TVG as active. A magma chamber may still exist beneath TVG (Konstantinou et al., 2007) and volcano-seismic signals, such as torminos, and earthquakes induced by variations of fluid pressure have been recorded by the TVG seismic network (Konstantinou et al., 2007; Lin et al., 2005; Rontogianni et al., 2012). Nevertheless, Wen et al. (2012) suggested that the magma chamber is a remnant of a past magma intrusion, now undergoing a cooling process. This agrees with the study of Lee et al. (2008), claiming that new magma supply in the chamber is unlikely. Wen et al. (2012) concluded that a volcanic eruption may preferentially occur as a consequence of the rupture of one of the two active faults that cross TVG rather than the activity of the magma chamber itself.

These recent findings prompted the realization of a research project called “Understanding the life of TVG” aiming at a better knowledge of TVG. Aside from the importance of this project in terms of basic science, a better assessment of the eruption hazard of TVG is also a societal need since this volcanic edifice overhangs the densely populated basin of Taipei as well as two nuclear power plants. Under this project, a superconducting gravimeter (SG, serial number T049, manufactured by GWR Instruments, Inc.; SG49 for short) has been installed on the Yangmingshan (Fig. 1, site name: YMSG), one of TVG’s mounts, in April 2012. An SG is a relative gravimeter, which provides continuous gravity time series with a long-term stability (Goodkind, 1999). The analysis of gravity time series is a way to monitor and quantify mass...

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redistributions. It has proven useful in various studies, including earthquake-induced deformation (Imanishi et al., 2004), global isostatic adjustment, tectonics (Francis et al., 2004), hydrology (Creutzfeldt et al., 2008), active fault assessment (Lien et al., 2014), and volcanoes monitoring (Jousset et al., 2000; Carbone et al., 2003). YMSG was set to determine whether or not magma flows exist beneath TVG. In addition to superconducting gravity measurements, time-lapsed gravity measurements by absolute gravimeters (AGs) have also been collected at the same location since 2005, providing a calibration factor and gravity references for YMSG data.

Numerous factors may cause gravity changes at a gravity site (Torge, 1989). One critical factor is the seasonal groundwater redistribution, which may be difficult to quantify precisely yet often responsible for the second largest gravity variations next to the tides. It is thus important to properly model the off-target sources before analyzing gravity changes due to magma movements (Kazama and Okubo, 2009). To this aim, we take advantage of rainfall data and water table data both acquired in the TVG area. We first detail how we process the superconducting and absolute gravity data and then describe how hydrological data are used to analyze gravity time series. After correcting this time series from seasonal hydrological effects, we discuss the gravity residuals in terms of volcanic and hydrothermal processes at TVG.

2. Data

2.1. Gravity data

The YMSG gravity time series that we use spans 3 years, from April 2012 to April 2015 (Fig. 2a). We use TSOFT package (Van Camp and Vauterin, 2005) to remove spikes from the gravity time series. TSOFT also computes and removes the pole tide using pole coordinates provided by IERS (the International Earth Rotation and Reference Systems Service at ftp://hpiers.obspm.fr/iers/eop/eopc04/). Tidal effects (both solid-Earth tides and ocean tide loading) were removed using TSOFT and tidal parameters obtained with the ETERNA package (Wenzel, 1996). The effect of air pressure changes on gravity was removed based on Boy et al. (2002) model and collocated pressure data. The AG values were measured with FG5 gravimeters (Niebauer et al., 1995) at the same location as YMSG and corrected for polar motion and atmospheric pressure similarly as for the SG data. Tidal effects are removed using the tidal parameters obtained from the SG tidal analysis, through the g software (Microg-LaCoste, 2008). Two different FG5 (serial numbers #224 and #331) were used: #224 from 2005 to 2010 (except on 7 May 2009) and #331 since 2011 and on 7 May 2009. One AG measurement session lasted 1 to 2 days, consisting of at least 30 sets. One set contains 100 drops in 30 min (one drop every 5 s starting at half of an integral hour).

The corrected YMSG and AG data are shown in Fig. 2b and c, respectively. The YMSG time series contains several gaps and steps, which may come from electronic or power disruptions (Hinderer et al., 2007; Van Camp and Francis, 2007). Each continuous YMSG data segment between two gaps can be offset independently along the gravity y-axis. (In Fig. 2b we have applied nominal step corrections only to make the display more convenient. See later.)

2.2. Hydro-meteorological data

Taiwan’s climate is influenced by the East Asian monsoons and their heavy rains (Chen and Chen, 2003). Therefore, local groundwater redistribution is likely to account for a large part of the residual gravity signal, as it has been shown for several others locations (e.g. Jacob et al., 2008; Longuevergne et al., 2009). We evaluate this contribution using two hydro-meteorological datasets recorded in the vicinity of YMSG (Fig. 1): 1. Hourly rain gauge measurements at station C0A86 (Fig. 2d) retrieved from the Data Bank for Atmospheric Research at the Taiwan Typhoon and Floods Research Institute (https://dbar.tffi.narl.org.tw/).

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2. Water table measurements at station TB-MW-23, at a 15-minute sampling interval (since April 2012, Fig. 2e). The water table varies in response to both the water input (rainfall) and output (subsurface run-off, evapotranspiration) in the watershed.

These data are used below to compute a "hydro-gravity model," that is, a model of gravity variations due to local water flow only.

2.3. Ground displacements data

Ground displacements are another valuable information when studying volcanic areas; previous studies have shown that ground displacements can be generated either by magma (Rymer et al., 1995; Beauducel and Cornet, 1999; Jouset et al., 2003) or by hydrothermal water movements (Battaglia et al., 2006; Fournier and Chardot, 2012). Such displacements can be measured by precise levelling surveys (e.g., Amaro and Chiarabba, 1995), interferometric synthetic aperture radar (InSAR, e.g., Solaro et al. (2010)), or GPS surveys (Puglisi et al., 2001). Six continuous GPS stations were operational at TVG in the entire time period of this study (2005–2015); displacement data, computed in the IGS08 frame (Rebischung et al., 2012) are available through the GPSLAB website (gps.earth.sinica.edu.tw/). Ground displacements records for the three components north, east and up are in Fig. 3.

Ground displacements at TVG are controlled to first order by tectonics (Yu et al., 1997; Shyu et al., 2005) which is responsible for the long-term linear trends on the north and east components. In addition, seasonal displacements are attributed to atmospheric and hydrologic loading (Dong et al., 2002). The long-term trend of the ground vertical displacements recorded by the YMSM permanent GPS station (Fig. 3, lower right panel), collocated with YMSG is 0.5 ± 0.1 mm yr\(^{-1}\). This is equivalent to −0.1 μGal yr\(^{-1}\) using the theoretical Bouguer corrected gradient of −0.2 μGal mm\(^{-1}\) (De Linage et al., 2007; Van Camp et al., 2011). Since the YMSG time series is rigorously continuous for at most 8 months (from October 2012 to July 2013), this long-term vertical displacement would make at most a deviation of 0.07 μGal. We can reasonably neglect this trend when analyzing the YMSG time series.

3. Hydro-gravity modelling

3.1. Porosity of the ground

Since aquifers are primarily recharged by rainfalls, we first investigate the correlation between rainfall measurements at COA86 and water table variations at TB-MW-23. We use Eq. (1) to estimate the water table variations \(\hat{h}_{\text{est}}\) at time \(i\) (Crossley et al., 1998):

\[
\hat{h}_{\text{est}} = r_j \left(1 - e^{-(i-j)/\tau_1}\right)e^{-(i-j)/\tau_2}
\] (1)

That is, the thickness \(\hat{h}_{\text{est}}\) of water at a given time \(i\) depends on the amount of rain \(r_j\) accumulated over past times \(j\) (given by COA86 data), considering that this rainwater infiltrates the ground with a charge time constant \(\tau_1\) and is released with a discharge time constant \(\tau_2\), regardless of the processes responsible for this release. We first compute the correlation coefficient between this model of water layer thickness (\(\hat{h}_{\text{est}}\)) and the measured changes of water table (\(h_{\text{in}}\)), testing \(\tau_1\) values ranging from 60 to 500 h and \(\tau_2\) values ranging from 150 to 2100 h. A maximum correlation coefficient of 0.92 between \(h_{\text{est}}\) and

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\( h_{\text{max}} \) is computed for \( \tau_1 = 190 \text{ h} \) (8 days) and \( \tau_2 = 800 \text{ h} \) (33 days). The correlation coefficient is very close to 1 and shows that the rainfall data at COA86 and Eq. (1) are adequate to explain water table variations. However, one must multiply the results from Eq. (1) by a factor of 10 in order to match the amplitude of the water table variations (Fig. 4). We conclude that the porosity of the aquifer is 10%; that is, the net mass variation of the actual water is 10% of the apparent well level variation. This porosity value is consistent with the dominantly andesitic constitution of TVG (Belousov et al., 2010); fresh andesite having a porosity of approximately 8%, which can be increased by weathering and fracturation (Jamtveit et al., 2011).

Note that two nearby rainfall gauges exist on TVG, COA87 and COA4, that are located on different hill slopes (Fig. 1). We tested them in the same way as for COA86 but obtained lower correlations between the estimated water table variation and the observed. Thus we conclude that the rainfall at COA86 better represents the local rainfall regime at the location of the well TB-MW-23.

### 3.2. Hydro-gravity model constrained using YMSG data

The YMSG gravity time series (Fig. 2b) shows a signal of daily variability (high frequency) superimposed by a signal which changes over a period of several months (low frequency), although not strictly periodic. In this part we build a hydro-gravity model by summing the gravity effect of the water table variations and the gravity effect of the rain soon after it reaches the ground. The rain is considered to be responsible for the high frequency signal and the water table variation is responsible for the low frequency signal.

#### 3.2.1. Gravity effect of the water table variations: low frequency model

We use the water table variations measured at the well TB-MW-23. The well being located about 1300 m from YMSG (Fig. 1), we assume its data can be used as a proxy of water table variations underneath YMSG. Since there is no constrain on the geometry of the aquifer, we
Therefore, we model the water table variations as a cylinder of radius 500 m, using (Hofmann-Wellenhof and Moritz, 2006):

\[ g_{\text{Bouguer}} = 2\pi G \rho \Delta h^\text{w} \]  

(2)

where \( G = 6.67 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2} \) is the universal constant of gravitation, \( \rho = 1000 \text{ kg m}^{-3} \) the volumetric mass of water, and \( \Delta h^\text{w} \) is the actual water table variation measured at TB-MW-23 divided by 10 to account for the rock porosity (estimated from water table variations, rainfall data and Eq. (1), see Section 3.1). However, this model significantly overestimates the gravity changes observed at YMSG (Fig. 5a, red and green lines), with a root mean square (rms) error of 6.8 μGal. To avoid this overestimation, we refine the aquifer model by making its lateral extension finite instead of infinite. Therefore, we model the water table variations as a cylinder of radius \( a \), thickness \( \Delta h^\text{w} \) and depth \( c \) (\( c \) is the distance from YMSG elevation and the bottom of the cylinder). The gravity effect \( g_{\text{cyl}} \) is computed for \( a \)-values ranging from 10 to 200 m and \( c \)-values ranging from 10 to 500 m, using (Hofmann-Wellenhof and Moritz, 2006):

\[ g_{\text{cyl}} = 2\pi G \rho \left( h_{\text{w}} + \sqrt{a^2 + (c-h_{\text{w}})^2} - \sqrt{a^2 + c^2} \right) \]  

(3)

The best fit is obtained with \( a = 120 \text{ m} \) and \( c = 130 \text{ m} \). The rms error is reduced to 2.5 μGal with no presence of the overestimation of gravity variation (Fig. 5a, red and purple curves). But this model does not capture the high frequency component of the gravity time series, which will be computed using the rainfall data.

### 3.2.2. Gravity effect of the rainwater at the surface: high frequency model

Here we use the rainfall data and Eq. (1) to compute the thickness of an equivalent layer of water \( h^\text{f} \), corresponding to the water located in the unsaturated zone close to the surface (in Eq. (1), \( h^\text{w} \) is replaced by \( h^\text{f} \)). It is then converted into gravity effect \( g_i \), using the infinite Bouguer plate approximation. Keeping the time index \( i \) already mentioned in Eq. (1) we have:

\[ g_i = 2\pi G \rho h^\text{f} \]  

(4)

The values of the time constant \( \tau_1 \) and \( \tau_2 \) are unknown, thus we have to test them, with \( \tau_1 \) ranging from 0.1 to 5 h and \( \tau_2 \) ranging from 1 to 220 h, until the model best fit the data. This method can create a high frequency signal compatible with that observed in the YMSG data. The last step is to combine this high-frequency model with the low frequency model (Section 3.2.1).

### 3.2.3. Combination of the low and high frequency models into one single hydro-gravity model

This combination consists in estimating all the parameters of the two previous models, namely \( a \) and \( c \) for the low frequency model (Eq. (3)), and \( \tau_1 \) and \( \tau_2 \) for the high frequency model (Eqs. (1) and (4)). In practice, the entire ranges of \( \tau_1 \) and \( \tau_2 \) values are tested for each set of \( a \) and \( c \). Then we sum the high and low frequency models and compare this sum to the YMSG time series. The rms is computed for each test of \( \{a, c, \tau_1, \tau_2\} \). Eventually, we find the lowest rms (1.4 μGal) upon the selected parameters \( \tau_1 = 0.2 \text{ h} \) (12 min), \( \tau_2 = 50 \text{ h} \), \( a = 70 \text{ m} \) and \( c = 90 \text{ m} \) (Fig. 5b). The residuals have a Gaussian distribution between −4.4 and 5.7 μGal and centered on 0, suggesting that this hydro-gravity correction is adequate (Fig. 5c). To summarize, at any given time, the majority of the residual gravity signal (without

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**Fig. 5.** (a) Comparison of the YMSG gravity data (red) with the Bouguer plate model (green) and the cylinder model (purple), both constrained only by the water table variations measured at TB-MW-23. (b) Comparison of the YMSG data (red) with the hydro-gravity model (blue), constrained by the water table variations and the rainfall data. The steps in the YMSG data (see Fig. 2b) were removed by adjusting the continuous YMSG segments to the hydro-gravity model. The absolute gravity (AG) data, considered as reference values, are also superimposed (green dots). (c) YMSG residuals after removing the hydro-gravity model, both in time and histogram views. Times when typhoons made landfall on Taiwan are shown with vertical green lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
tidal, atmospheric and pole tide effects) at YMSG comes from water mass changes in two different parts of the ground: the unsaturated zone located near the ground surface and the deeper aquifer.

As seen in Fig. 2b, due to several gaps and steps, the original YMSG time series is not rigorously continuous and segments were kept separated from each other. In Fig. 5a we shift them along the gravity axis until they overlap the hydro-gravity model. This method allows us to correct steps in a non-arbitrary way that is reasonable since we assume that gravity changes are primarily due to local water redistribution. On the other hand, it may also remove from the YMSG data any long-term gravity trend that would not be due to the computed groundwater redistribution. The first long-term gravity trend to consider is the instrumental drift of YMSG. It has no geophysical meaning and can be estimated by comparing the YMSG time series with AG data measured at the same location, as a FG5 gravimeter does not suffer from instrumental drift (Hinderer et al., 2007). The drift of a SG can be exponential or linear with time, although Van Camp and Francis (2007) showed that an exponential model should be preferred for records longer than 10 years. In our case, the only option is to compare YMSG and AG data on a time period where the YMSG measurements are continuous, without gaps or steps. This corresponds to a 6-months period, from October 2012 to April 2013, during which three AG measuring campaigns were carried out (Fig. 5b). This small amount of AG data, combined with the AG’s standard deviation, leads to an instrumental linear drift of $9.2 \pm 14.8 \mu\text{Gal}\cdot\text{yr}^{-1}$ that we decided not to remove from the YMSG data because of its very large uncertainty. The consequence is that we cannot rely on the YMSG time series for identifying long-term gravity linear trends that may yet exist at TVG, as a result of tectonic or slow volcanic processes. This could be fixed by increasing the frequency of AG measurements.

In Fig. 5b and c, the largest residuals are mostly found during the summer season, which experiences extraordinarily heavy rains due often to typhoons. Time-independent parameters of the hydro-gravity model for the three years of YMSG data may not be proper to predict the groundwater redistribution during the short periods of heavy rains. We test this hypothesis by assessing the hydro-gravity model parameters in the summers (June to September) of 2012 and 2013, not in summer 2014 since YMSG data are missing in August 2014. There is no reason to change the location of the aquifer, hence we keep $a = 70$ m and $c = 90$ m. Rather, we re-estimate the effect of the water in the unsaturated zone by varying $\tau_1$ and $\tau_2$. We find that summer’s gravity variations are better modelled (lower rms) with $\tau_2 = 130$ h in summer 2012 and $\tau_2 = 150$ h in summer 2013, while $\tau_1$ stay unchanged (Fig. 6 and Table 1).

This implies that the processes responsible for the release of water from the unsaturated zone take about 3 times longer in summer than during the rest of the year, likely as a consequence of the heavier input of water. Thus the large gravity residuals during the 2012 and 2013 summer seasons seem to be due to an imperfection of our hydro-gravity model rather than due to a volcanic event, such as a

![Fig. 6](image-url)
magma transfer at depth. Nevertheless, the overall agreement between the YMSG data and our hydro-gravity model suggests that this model is adequate. That is, the gravity variations at YMSG are due to local seasonal hydrology and have at least two components: the immediate effect of the rainwater flowing into the unsaturated zone, which triggers gravity change as soon as the rain reaches the ground surface, and the effect due to the water table variations, which is delayed by the time needed for the rainwater to accumulate in an aquifer. The unsaturated zone acts as a low-pass filter for rain-induced gravity signal.

3.3. Hydro-gravity model before the installation of YMSG

To further test the hydro-gravity model, we compare it to the 23 AG measurements collected at the location of YMSG over 2005–2015. No well log data exist before 2012, but we have shown in Section 3.1 that water table variations can be predicted using rainfall data measured at C0A86 and Eq. (1), using $\tau_1 = 190$ h (8 days) and $\tau_2 = 800$ h (33 days). This can be used to estimate the missing water table measurements during 2005–2012, as C0A86 measurements started in 1995. We thus have an estimation of the water table variations and the rainfall data. Eventually we combine these two datasets using the method and parameters $[a, c, \tau_1, \tau_2]$ given in Section 3.2 and get the hydro-gravity model since 2005 (Fig. 7).

The hydro-gravity model is in agreement with 74% (17 out of 23) of the AG measurements. Outside the YMSG measurement time period (during which the YMSG data were used to constrain the hydro-gravity model), this model still matches 60% (9 out of 15) of the AG data. In particular, the 35 ± 3 μGal gravity change measured from May 2006 to January 2007 is at least twice larger than any other gravity change over the entire period. This suggests that some large mass redistribution due to processes other than seasonal hydrology may have occurred in this time period.

4. Large mass transfers between 2005 and 2007

4.1. Fluid circulation supported by seismological and geochemical studies

The 2005–2007 large gravity changes (Fig. 7) are concomitant to seismological and geochemical noticeable events (Fig. 8a and b). Lee et al. (2008, 2016) observed a significant increase of the $\text{SO}_2/\text{H}_2\text{S}$ ratio from July 2005 to July 2007, only at the Dayoukeng fumarole. To explain this increase, Lee et al. (2008) suggested that more magmatic gases contributed to the fumaroles as water from the primary hydrothermal system, depicted as a deep water reservoir located close to the magma chamber, was supplied to the Dayoukeng fumaroles through fracture openings. In the seismological records, Rontogianni et al. (2012) identified several spasmodic bursts, defined as “rapid-fire sequences of brittle-failure earthquakes with overlapping coda” (Hill and Prejean, 2005). They are induced by an increase of pore pressure due to fluid circulation through cracks and most of them were recorded between 2006 and 2007. It is interesting to note that these spasmodic bursts occurred in the region of a highly fractured former magma passage (Fig. 8b) parallel to the Chinshan fault as evidenced by seismic tomography (Wen et al., 2012). This passage lies beneath Dayoukeng fumarole and the YMSG site, and extends between 0 and 4 km depth in this area.

4.2. No significant ground displacements

We mentioned in Section 2.3 that ground displacements at TVG are controlled to first order by tectonics and seasonal atmospheric and hydrologic loading. These effects are modelled using a combination of linear and sinusoidal functions (Fig. 9, left panel), which are computed one measurement in July 2010, which deviate from the model by up to 21 ± 2 μGal. In particular, the 35 ± 3 μGal gravity change measured from May 2006 to January 2007 is at least twice larger than any other gravity change over the entire period. This suggests that some large mass redistribution due to processes other than seasonal hydrology may have occurred in this time period.

### Table 1

Synthesis of the values of $\tau_1$ and $\tau_2$ for the original hydro-gravity model and for the hydro-gravity model computed only using the summer period YMSG data, in 2012 and 2013, with rms in each case.

<table>
<thead>
<tr>
<th></th>
<th>Original model</th>
<th>Modified model (focused on Summer)</th>
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<tbody>
<tr>
<td></td>
<td>$\tau_1$ (hours)</td>
<td>$\tau_2$ (hours)</td>
</tr>
<tr>
<td>Summer 2012</td>
<td>0.2</td>
<td>50</td>
</tr>
<tr>
<td>Summer 2013</td>
<td>0.2</td>
<td>50</td>
</tr>
</tbody>
</table>

![Fig. 7. Hydro-gravity model computed since 2005 (blue line) using rain gauge C0A86 data and compared to gravity variations measured using an absolute gravimeter (AG data, green dots). The vertical grey lines correspond to 399 hourly rain gauge measurements failures between 2006 and 2008 (2% of missing data). In particular, there is no data during the first 15 days of January 2008. Small left-arrows point AG measurements that deviate the most from the hydro-gravity model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](image-url)
with the CATS program (Williams, 2008). Once these effects are removed from the GPS solutions, the residual displacements observed in the 2005–2007 time period, for the vertical or horizontal components are at the mm level (Fig. 9, right panel).

Assuming an elastic rheology, we assess the magnitude of the displacements that might be associated with the gravity variations observed between 2005 and 2007. The average instrumental uncertainty $\delta_{AG}$ is 3.6 μGal from the standard deviation of the AG measurements.

Fig. 8. (a) Gravity residuals after removing the hydro-gravity model (Fig. 7) along with other evidences of volcanic or hydrothermal activity reported in geochemical and seismological studies (Lee et al., 2008; Rontogianni et al., 2012; Pu et al., 2014). (b) Localization of the 2006–2007 spasmodic bursts (red dots). The magma passage runs all along the south east part of Chinshan fault (Wen et al., 2012), beneath the cluster of spasmodic bursts, YMSG and the fumaroles (blue triangles). Inverted black triangles are permanent GPS stations. One is collocated with YMSG (name YMSM). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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We add two uncertainty sources for the gravity changes in the 2005–2007 period, both related to the hydrological corrections described in Section 3: the first one is the rms misfit $\delta_{\text{hyd}} = 1.4$ $\mu$Gal between the hydro-gravity model and the YMSG data (see above). The second one is due to the misfit between the water table change estimated from the rainfall data (Fig. 4) and the actual one, or $\delta_{\text{wat}} = 3.1$ $\mu$Gal. Altogether, they lead to a total uncertainty $\delta_{\text{TOT}} = \sqrt{\delta_{\text{hyd}}^2 + \delta_{\text{wat}}^2} = 5$ $\mu$Gal, to be associated with the residual gravity changes during 2005–2007.

This gravity change $\Delta g$ is then decomposed into three time period segments:

- **Period 1**, from $t_1$ (09-11-2005) to $t_2$ (27-05-2006): $\Delta g_1 = -22$ $\mu$Gal
- **Period 2**, from $t_2$ to $t_3$ (17-01-2007): $\Delta g_2 = 35$ $\mu$Gal
- **Period 3**, from $t_3$ to $t_4$ (01-08-2007): $\Delta g_3 = -16$ $\mu$Gal

The Mogi model gives relation between the vertical ground displacements ($\Delta h$) and the gravity changes as (Hagiwara, 1977; Jousset and Okada, 1999):

$$\frac{\Delta g}{\Delta h} = \beta + \frac{4}{3} \pi G \rho_0$$

(5)

where $\rho_0$ is the mean density of the mass responsible for the gravity change and $\beta$ is the free-air effect due to the gravity measurement site vertical displacements ($\beta = 308.6$ $\mu$Gal·m$^{-1}$). We compute $\Delta h$ for the above-listed three values of $\Delta g$ and for a range of $\rho_0$ from 1000 (for water) to 2500 km·m$^{-1}$ (for nominal magma).

![Fig. 9. Vertical, East and North components at the six continuous GPS stations on TVG (Fig. 8b). The original data are on the left panel, along with a fit for both a long-term (linear) and a seasonal (sinusoidal) trend (blue line). The de-trended data are on the right panel, with a 90-days smoothing (red line). The vertical black lines bound the 2005–2007 time period where large gravity changes are observed at YMSG and the vertical dotted black lines show the exact time of the four AC gravity measurements done in this time period. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](image-url)

Fig. 10 shows that several centimeters of vertical displacements are expected from this model. In particular, the maximum gravity change, between May 2006 and January 2007, should result in as much as 9 cm of uplift at YMSG. Such a vertical displacement is not observed; the ground displacements at YMSG fluctuated within less than $\pm 1$ cm (Fig. 9, bottom right panel). The model for Eq. (5) considers a spherical shape for the material moving beneath the surface. Since TVG is located in a tectonically active and faulted area, alternatively the material responsible for the gravity changes at YMSG can be considered to move through fractures as theorized by Sasai (1986, 1988) where specific fault configurations can return lower ground displacements for a given gravity change than the Mogi model. Jousset et al. (2003) demonstrated that the fracture filling model was more efficient than the Mogi model in reconciling $\Delta g$ and $\Delta h$ data acquired at Usu volcano (Japan) before and after its 2000’s eruption. Still, uplift of the order of several cm and horizontal displacements up to 10 cm should be present for the model due to the elastic deformation of the rock in which some material is forcing its way. Thus, to explain the absence of surface displacement at TVG, we hypothesize that the material can move in an existing network of open fractures. Evidences of such a mechanism were found at Etna volcano between June 1990 and June 1991, when magma entered a pre-existing fracture system that can remain open between eruptions (Carbone et al., 2003; Rymer et al., 1993). At TVG, this fracture system can be identified with the above-mentioned highly fractured magma passage (Wen et al., 2012). It is parallel to the Chinshan fault, an active normal fault materializing the extensional tectonics of the north-eastern Taiwan (Chang et al., 2003b; Huang et al., 2012; Shyu et al., 2005). Although no fracture orientation measurements are available in this area, one can reasonably suppose...
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that this extensional tectonics builds the stress needed for maintaining the fractures open. Barton et al. (1995) showed that the permeability of critically stressed faults is much higher than that of faults that are not optimally oriented for failure in the current stress field. As a result, such a fractured medium can be considered as a network of efficient fluids conduits, allowing significant material transfers in the ground. It is not possible with our data to rigorously demonstrate that this fluid is magma or hydrothermal water. Otherwise, the coupling ground displacements and gravity changes would have been an efficient way to infer the density contrast of the fluid with the host rocks (Jousset et al., 2003; Sasai, 1986).

In the rest of this study we will thus use the generic term “fluid”, instead of water or magma. Given that, we note that previous TVG studies conducted in 2005–2007 have in most cases suggested hydrothermal circulations rather than magma movements (Konstantinou et al., 2007; Lee et al., 2008; Rontogianni et al., 2012).

4.3. Fluid circulation model

Fluid ascent beneath TVG was believed to be responsible for both the gas composition changes in Dayoukeng fumarole and the occurrence of spasmodic bursts recorded during 2005–2007 (Lee et al., 2008; Rontogianni et al., 2012). We adopt this hypothesis as model A (fluid ascension) to explain the residual gravity changes, according to which most of the spasmodic bursts had occurred in a radial distance (x) between 1000 and 2000 m from YMSG and a depth (z) between 0 and 2 km. These geometric parameters are used to compute the mass transport that is responsible for the observed gravity change $\Delta g$ under the hypothesis that this extensional tectonics builds the stress needed for maintaining the fractures open. Barton et al. (1995) showed that the permeability of critically stressed faults is much higher than that of faults that are not optimally oriented for failure in the current stress field. As a result, such a fractured medium can be considered as a network of efficient fluids conduits, allowing significant material transfers in the ground. It is not possible with our data to rigorously demonstrate that this fluid is magma or hydrothermal water. Otherwise, the coupling ground displacements and gravity changes would have been an efficient way to infer the density contrast of the fluid with the host rocks (Jousset et al., 2003; Sasai, 1986).

In the rest of this study we will thus use the generic term “fluid”, instead of water or magma. Given that, we note that previous TVG studies conducted in 2005–2007 have in most cases suggested hydrothermal circulations rather than magma movements (Konstantinou et al., 2007; Lee et al., 2008; Rontogianni et al., 2012).

Table 2

<table>
<thead>
<tr>
<th>Time $t_i$</th>
<th>Model A: Ascending fluid</th>
<th>Model B: Cycling fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$ (m)</td>
<td>$z$ (m)</td>
<td>$x$ (m)</td>
</tr>
<tr>
<td>Time $t_1$</td>
<td>1100 ± 100</td>
<td>1200 ± 200</td>
</tr>
<tr>
<td>Time $t_2$</td>
<td>2000</td>
<td>750 ± 50</td>
</tr>
<tr>
<td>Time $t_3$</td>
<td>1000 ± 100</td>
<td>650 ± 50</td>
</tr>
<tr>
<td>Time $t_4$</td>
<td>1100 ± 100</td>
<td>400 ± 100</td>
</tr>
<tr>
<td>Minimum mass of fluid (Mt)</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

Fig. 10. Ground displacements computed using Eq. (4) for the three largest gravity changes measured at YMSG (blue lines), assuming a Mogi source model. a, b and c refer to the gravity changes listed as steps 1, 2 and 3, respectively. Black lines correspond the 5 $\mu$Gal uncertainty on the gravity measurements, converted into displacements. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 11. Scheme of the fluid circulation models that fit the gravity changes observed at YMSG. Values x (radial distance from the gravimeter) and z (depth) are given in Table 2. Numbers 1 to 4 refer to the time of the absolute gravity measurements and the values in $\mu$Gal are the gravity changes measured between each time. Areas experiencing spasmodic bursts are in red (see Fig. 8b for a map view). Here we suggest that the fluid ascended toward Dayoukeng fumarole through a dense network of existing fractures located in a former magma passage. At time 3, the fluid either continues upward either goes downward, back to its initial location at time 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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the geochemical changes observed in this fumarole, suggesting that the 2005–2007 fluid circulation affected it.

5. Discussion

5.1. Limitation of the gravity modelling

The gravity modelling in Section 4.2 was done using purposely a point source gravity effect in order to minimize the amount of unknown parameters to be sought: mass, radial distance and depth of this mass relative to YMSG. Since there is only one single site of gravity measurements and no ground displacements, multiple solutions are possible while none can be favored. Moreover, the geometry of the underground fluid reservoir is probably more complex and can result in considerable differences between actual and estimated volumes (Fialko et al., 2001). As a test, we build penny-shaped reservoirs, whose radius is arbitrarily set to be 10 times larger than their thickness while keeping the centers and volumes the same as for the point-source models given in Table 2. Their gravity effect is computed using analytic formulas from Singh (1977). We find that the computed gravity value $\Delta g_1$, $\Delta g_2$ and $\Delta g_3$ deviates by 9%, −12% and 58%, respectively, from Model A, and by −4%, −6% and 6% from Model B. This deviation can result in either changes of the location or the mass of the fluid flowing in the ground, especially for Model A, where the fluid keeps ascending during the entire 2005–2007. Ground displacements, if exist, together with the gravity changes, provide useful constraints on the path of material movement at depth in terms of its volume (e.g. Bartel et al., 2003; Beauducel and Cornet, 1999) and density (Battaglia et al., 2006, 1999; Jousset et al., 2003, 2000). Their very low amplitudes here prevent us from considering the elastic rheology and hence an unequivocally revelation of the scenario of the fluid mass transport. One way to overcome these uncertainties is to measure gravity time series at several other sites around YMSG, a possibility as soon as YMSG gravity time series shows significant deviations from the hydro-gravity model proposed in Section 3. At present, while the large gravity changes show little doubt that mass transports did occur in TVG, the suggested models in Section 4.2 must be regarded as tentative.

5.2. Timing of the absolute gravity measurements

Before 2012, the gravity time series is sporadic, for which we interpret the large gravity changes between 2005 and 2007 using the first AG measurement done in November 2005 as a reference. However, Lee et al. (2008) have observed changes of the Dayoukeng fumarole composition and temperature as early as August 2004 prior to any gravity measurement. One could thus question the validity of using the first AG measurement as a reference, even though it has the same value (within the uncertainty) as the AG values measured after the 2005–2007 event. It is unknown whether mass transport was already ongoing during November 2005 but the gravity value was the same as during the rest of the time period after August 2007. On the other hand, we note that, because of the discontinuity of the gravity measurements, the actual extreme values of the 2005–2007 gravity changes could be higher than the apparent measured values.

Pu et al. (2014) identified a swarm of earthquakes related to volcanic or hydrothermal activity nine months before, in October 2009, and the SO$_2$/H$_2$S ratio increased again between February 2010 and February 2011 (Lee et al., 2016). The single gravity measurement of July 2010 which showed an apparent gravity drop is the only one over a period of nearly 17 months (from 9 February 2010 to 20 June 2011). Assessing a mass transport from one single gravity measurement is not reasonable and the question whether another fluid movement occurred within the TVG hydrothermal system in 2010 remains open. YMSG provides nearly continuous gravity measurements that will enable us to observe a complete cycle of gravity changes if a new hydrothermal cycle occurs in the coming years. To finish, the process that triggered this fluid migration is not known but it might be related to Taiwan’s high seismicity under its active tectonics. Indeed, Pitt and Hutchinson (1982) proposed that an increase of the seismic activity beneath the hydrothermal system of the Mud Volcano at Yellowstone National Park could have expanded the pre-existing fracture system, thus enhancing fluid flows. Similarly, at the Juan de Fuca mid-oceanic ridge, Johnson et al. (2000) observed the activity of hydrothermal vents a few days after an earthquake swarm of tectonic origin. However, this hypothesis is difficult to test as Taiwan experiences tectonic earthquakes on a daily basis, preventing from finding relevant time correlations between these earthquakes and the fluid circulations.

6. Concluding remarks

The gravity variations recorded at TVG since 2005 primarily reflect the local redistribution of water. They can be considered as the sum of a daily signal, due to the immediate effect of rains infiltrating the unsaturated zone and a pluri-months signal controlled by the water table variations. Besides, the water table variations can also be properly reconstructed only using rainfall data, and it suggests that the aquifer’s porosity is 10%. Once this hydrological effect is removed from the gravity time series we find large gravity residuals between 2005 and 2007, which show the occurrence of mass transfers not related to seasonal hydrology. These gravity changes are concomitant to changes of the geochemical composition of the Dayoukeng fumarole (Lee et al., 2008) and to an increase of the occurrence of fluid-pressure induced spasmodic bursts (Rontognani et al., 2012). These gravity changes are interpreted as the consequence of fluid mass transport, probably due to hydrothermal circulations, although the data presented in this study cannot rigorously show that this fluid is water or magma. We propose that fluids circulate through a network of existing fractures hosted in a former magma passage that runs beneath TVG, parallel to the Chinsin Shan normal fault (Wen et al., 2012). The existence of such fractures is hypothesized because no clear surface ground displacements are observed by GPS during the gravity changes, suggesting that the material could move without increasing the ambient pressure. This absence of displacements results in a lack of constraints for inverting the mass and path of the material, which are thus inferred only using the value of the gravity change and the location of the spasmodic bursts. Several models are possible and we find that at least 15 Mt of material might have transported in the first 2000 m of the surface and at most 1000 m away (horizontally) from YMSG, among other possible scenarios. Aside from the confirmation of TVG’s 2005–2007 mass transport, the interest of this study is to propose a suitable hydro–gravity model that can help to rapidly notice any departure from the usual local gravity effect and identify future mass transfers due to hydrothermalism or magmatic processes at depth. Then, measuring time-variable gravity data at other sites on TVG, as soon as such a departure is identified, should permit to better unravel the path and mass associated to these processes.

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