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Three-dimensional thermal sensitivity analysis of cooling of a magma chamber in the Los Azufres geothermal field, Michoacán, Mexico

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Abstract

Background: We present three-dimensional simulation of cooling of 63 models of a magma chamber in the Los Azufres geothermal field by varying the top of the chamber depth between 5 and 9 km (centroid from about 7 to 13 km) and its volume between 300 and 600 km^3.

Methods: Nineteen new best-fit cubic equations are presented to represent the temperature field in the geothermal reservoir in terms of the chamber centroid depth, its volume, or both.

Results: These equations clearly show that the thermal regime is much more sensitive to chamber depth than to its volume. These simulation results imply that, for a better estimation of the energy budget of a volcanic area, the depth parameter should be better constrained than the chamber volume.
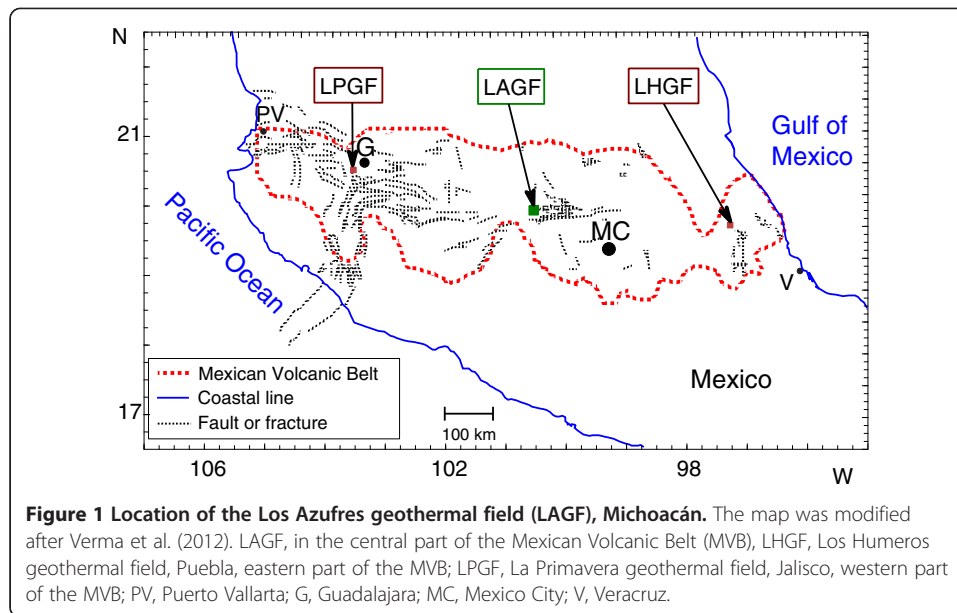
Conclusion: Geoscientists are, therefore, encouraged to obtain more reliable estimates of magma chamber depths for active volcanoes and potential geothermal areas. Furthermore, the smallest discretization time and mesh size should be used for solving the heat flow equations in three-dimensions.

Keywords: Thermal modeling; Subsurface temperatures; Geothermal system; Magma chamber; Three-dimensional simulation

Background

Three-dimensional thermal modeling of a magma chamber has been already applied to decipher thermal regime beneath the Los Humeros and La Primavera geothermal fields, located in the eastern and western parts of the Mexican Volcanic Belt, respectively (LHGF and LPGF, respectively, in Figure 1; Verma and Andaverde 2007; Verma et al. 2012; Verma and Gómez-Arias 2013a). Such a three-dimensional model has been also put forth for cooling of two magma chambers in the Las Tres Vírgenes geothermal field, Baja California Sur, Mexico (Guerrero-Martínez and Verma 2013).

The sensitivity of two magma chamber parameters - chamber depth and volume - was also evaluated by Verma et al. (2011) at the top of the magma chamber as well as at its sides, which indicated that the chamber depth is more sensitive than the chamber volume. Similarly, the influence of discretization time and mesh size was estimated from three-dimensional temperature field simulation in the LHGF and LPGF (Verma and Gómez-Arias 2013b).

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Figure 1 Location of the Los Azufres geothermal field (LAGF), Michoacán. The map was modified after Verma et al. (2012). LAGF, in the central part of the Mexican Volcanic Belt (MVB), LHGF, Los Humeros geothermal field, Puebla, eastern part of the MVB; LPGF, La Primavera geothermal field, Jalisco, western part of the MVB; PV, Puerto Vallarta; G, Guadalajara; MC, Mexico City; V, Veracruz.

For the Los Azufres geothermal field (LAGF in Figure 1) located in the central part of the Mexican Volcanic Belt, only two-dimensional thermal modeling was carried out long ago by Verma and Andaverde (1996). We present the first three-dimensional simulation study of this field and document the temperature regime in the underlying geothermal reservoir as a function of the chamber depth and volume. The reservoir temperatures are inferred to be much more sensitive to chamber depth than to its volume. This is the first study that evaluates the sensitivity of these two parameters for a geothermal reservoir. Six additional runs for the last thermal model are presented to predict the thermal regime of this geothermal area and to understand the influence of discretization time and mesh size.

Geological synthesis

The LAGF is located in the state of Michoacán, about 200 km NW of Mexico City, between approximately 100°38′ and 100°43′ W and 19°50′ and 19°45′ N, and covers an area of about 72 km^2 (Dobson and Mahood 1985). The geology and geochemistry of the area were reported by Campos-Enríquez et al. (2005), Cathelineau et al. (1987), Dobson and Mahood (1985), Pandarinath (2011), Pandarinath et al. (2008), Pradal and Robin (1994), Verma (1985), Verma and Andaverde (1996), and Verma et al. (2005), among others. The pre-volcanic basement consists of shales, sandstones, and conglomerates of Eocene to Oligocene age. The oldest volcanic rocks are andesites of Miocene age (about 18 to 6 Ma) followed by the eruption of rhyolites at 1.6 to 0.84 Ma and andesites at about 0.86 Ma.

Voluminous eruption of dacites (about 19.3 km^3) took place at about 0.36 to 0.33 Ma. This major event was simulated in our thermal modeling, which was carried out for about 0.40 Ma to the present. This large eruption was followed by about 12.2 km^3 of rhyolites during about 0.30 to 0.14 Ma and about 4.6 km^3 of the youngest basalt, considered to have erupted during 0.15 Ma to the present. From geochemical

modeling, Verma (1985) suggested that the volume of the magma chamber beneath the LAGF was at least about 400 km^3.

Methods

Conceptual models and methods

A region of 30 km (*x*-axis, north–south direction) × 30 km (*y*-axis, east–west direction) × 20 km (*z*-axis, vertical direction) was considered for 3-D simulator TCHEMSYS of Verma and Andaverde (2007). For thermal sensitivity analysis, uniform mesh size of 0.25 km × 0.25 km × 0.25 km was used, which resulted in 120 × 120 × 80 control volumes (a total of 1,152,000 volumes for solving heat-flow equations in three dimensions). Emplacement and boundary conditions as well as simplified geology are summarized in Table 1.

To evaluate the sensitivity of chamber depth and volume, 63 different simulation models were considered from nine chamber depths (top of the chamber at 5 to 9 km, with increments of 0.5 km) and seven chamber volumes (300 to 600 km^3, with increments of 50 km^3). All 63 models from M1 to M63 are summarized in Table 2. For example, the first nine models, M1, M2, M3, M4, M5, M6, M7, M8, and M9, correspond to the top of the magma chamber at the subsurface depths of 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5, and 9.0 km, respectively, and the chamber volume of 300 km^3 is for each of them. Three of these models, M1, M5, and M9, are graphically presented in Figure 2. Similarly, three of the final models, M55, M59, and M63, are shown in Figure 3. Discretization time of 500 years and total simulation time of 100,000 years were used for these 63 models. Cubic polynomial equations were fitted to the appropriate simulated results.

Similarly, six runs were carried out for discretization time of 20, 10, and 1 year, mesh size of 0.20 and 0.10 km, and total simulation time of 0.40 million years representing the entire eruption history of the main volcanic events (Dobson and Mahood 1985; Verma and Andaverde 1996). These runs were obtained for 5 km depth of the top of magma chamber, 600 km^3 of chamber volume, and three magma recharge events at 0.34 Ma (20 km^3 of magma), 0.22 Ma (12 km^3), and 0.026 Ma (5 km^3). The magma chamber depth and volume for these runs correspond to the model M55 (Figure 3).

Results and discussion

Evaluation of sensitivity of chamber depth and volume

Temperature versus depth (or control volume number) profiles for the 63 simulated models were similar to the one presented in Figure 4 corresponding to model M55 (Table 2). The magma chamber is schematically shown by continued lines. The diagram shows the temperature distribution along a vertical line (coordinates 80, 1 in the control volume space) of 20 km depth, at the center of the chamber (*x* = 60 and *y* = 60), i.e., between the surface (*x*, *y*, *z* coordinates 60, 60, 80) and the deepest part of the simulated volume (60, 60, 1). Note the thermal anomaly due to the emplacement and cooling of the magma chamber is still observed within the magma chamber, as well as both above and below it (compare filled diamonds and open squares with the normal geothermal gradient shown as a dotted line in Figure 4).

Figure 5 shows the results of simulated temperatures and temperature excess values (the difference of simulated temperatures and the normal subsurface temperatures)

Table 1 Emplacement conditions of magma chamber and geological properties for thermal models of the Los Azufres geothermal field (LAGF)

Physical property (units)	Emplacement of magma chamber
Emplacement conditions	
Depth of the top the chamber (d) (km)	5.0-9.0
Depth of the chamber centroid (dc) (km)	7.000 to 12.875
Volume (V) (km^3)	300 to 600
Thickness of the magma chamber (E) (km)	4.00 to 7.75
Radius (r) (km)	5.0
Magma emplacement temperature (T_{cham}) (°C)	1,350
Boundary conditions	
Surface temperature (T_s) (°C)	25
Geothermal gradient (ΔT_g) (°C/km)	30
Geological strata (strata 1–4 rock type)[a]	
Granite-granodiorite	
Width (km)	16.00
Thermal conductivity (W/mK)	2.80
Specific heat (J/kg K)	1,073
Density (kg/m^3)	2,680
Metamorphic rocks	
Width (km)	1.00
Thermal conductivity (W/mK)	2.73
Specific heat (J/kg K)	1,050
Density (kg/m^3)	2,280
Andesite	
Width (km)	2.75
Thermal conductivity (W/mK)	1.72
Specific heat (J/kg K)	1,151
Density (kg/m^3)	2,180
Rhyolite	
Width (km)	0.25
Thermal conductivity (W/mK)	3.44
Specific heat (J/kg K)	1,074
Density (kg/m^3)	2,460

[a]Physical properties were taken from Contreras et al. (1988) and Verma and Andaverde (1996).

along a vertical profile at the middle part of the simulated region for the same model as in Figure 4 (M55; Table 2). From these estimates, vertical thermal gradient (δT) values in the geothermal reservoir (subsurface depths of 1 to 2.5 km) were estimated for all 63 models.

Best-fit cubic equations for the thermal gradient as a function of the depth of the chamber centroid (dc) parameter (Equations 1 to 7) are listed in Table 3. The results of the models used for a given equation are also listed in the third column of Table 3. As an example, Equation 1 was obtained from the simulated results of models M1 to M9 (Tables 2 and 3). Equation 1 shows the behavior of simulated thermal (note 'thermal' and not 'geothermal' is used, because we have subtracted the initial 'normal' geothermal temperatures from the simulated temperatures) gradient in the geothermal reservoir

Table 2 Specifications of the 63 models of the Los Azufres geothermal field (LAGF) simulated in the present work
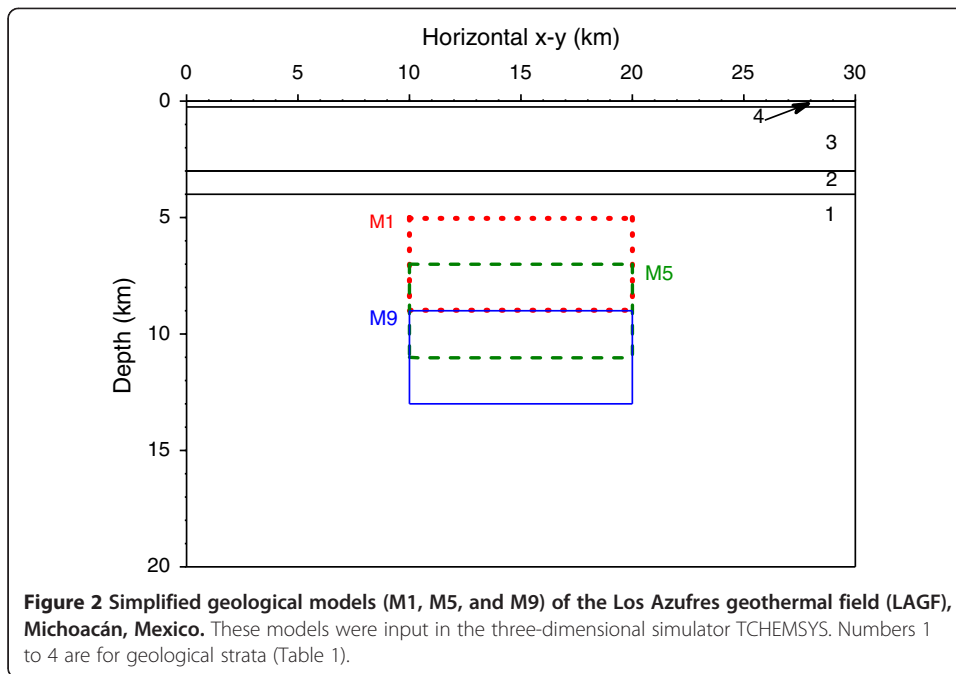
Model	Subsurface depth		Chamber volume V (km^3)	Thickness of the magma chamber E (km)
	Top of the chamber d (km)	Chamber centroid dc (km)		
M1	5.0	7.000	300	4.00
M2	5.5	7.500	300	4.00
M3	6.0	8.000	300	4.00
M4	6.5	8.500	300	4.00
M5	7.0	9.000	300	4.00
M6	7.5	9.500	300	4.00
M7	8.0	10.000	300	4.00
M8	8.5	10.500	300	4.00
M9	9.0	11.000	300	4.00
M10	5.0	7.250	350	4.50
M11	5.5	7.750	350	4.50
M12	6.0	8.500	350	4.50
M13	6.5	8.750	350	4.50
M14	7.0	9.250	350	4.50
M15	7.5	9.750	350	4.50
M16	8.0	10.250	350	4.50
M17	8.5	10.75	350	4.50
M18	9.0	11.250	350	4.50
M19	5.0	7.500	400	5.00
M20	5.5	8.000	400	5.00
M21	6.0	8.500	400	5.00
M22	6.5	9.000	400	5.00
M23	7.0	9.500	400	5.00
M24	7.5	10.000	400	5.00
M25	8.0	10.500	400	5.00
M26	8.5	11.000	400	5.00
M27	9.0	11.500	400	5.00
M28	5.0	7.875	450	5.75
M29	5.5	8.375	450	5.75
M30	6.0	8.875	450	5.75
M31	6.5	9.375	450	5.75
M32	7.0	9.875	450	5.75
M33	7.5	10.375	450	5.75
M34	8.0	10.875	450	5.75
M35	8.5	11.375	450	5.75
M36	9.0	11.875	450	5.75
M37	5.0	8.250	500	6.50
M38	5.5	8.750	500	6.50
M39	6.0	9.250	500	6.50
M40	6.5	9.750	500	6.50
M41	7.0	10.250	500	6.50
M42	7.5	10.750	500	6.50

Table 2 Specifications of the 63 models of the Los Azufres geothermal field (LAGF) simulated in the present work *(Continued)*
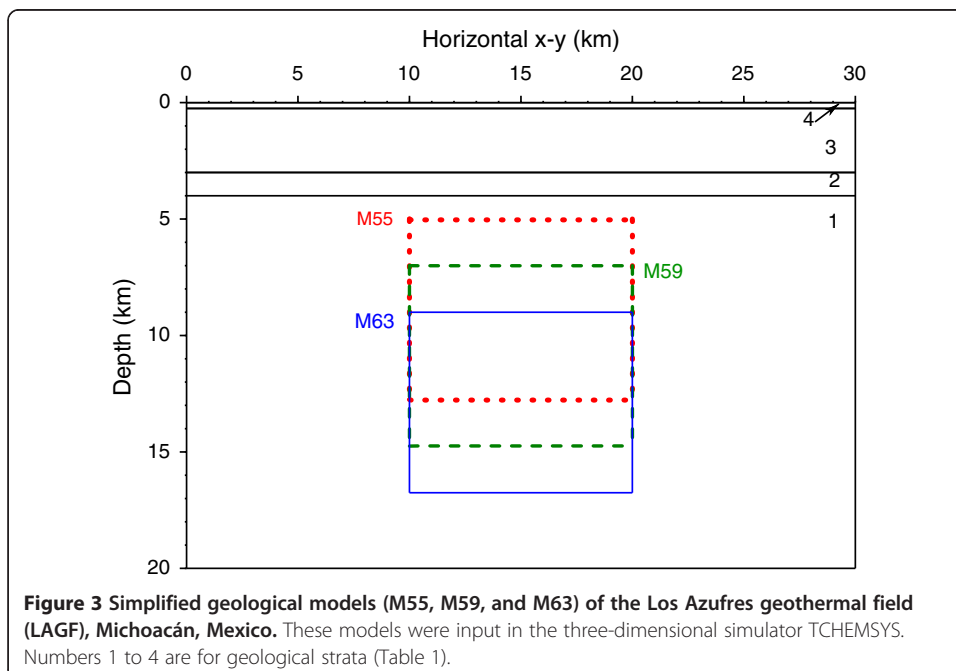
M43	8.0	11.250	500	6.50
M44	8.5	11.750	500	6.50
M45	9.0	12.250	500	6.50
M46	5.0	8.500	550	7.00
M47	5.5	9.000	550	7.00
M48	6.0	9.500	550	7.00
M49	6.5	10.000	550	7.00
M50	7.0	10.500	550	7.00
M51	7.5	11.000	550	7.00
M52	8.0	11.500	550	7.00
M53	8.5	12.000	550	7.00
M54	9.0	12.500	550	7.00
M55	5.0	8.875	600	7.75
M56	5.5	9.375	600	7.75
M57	6.0	9.875	600	7.75
M58	6.5	10.375	600	7.75
M59	7.0	10.875	600	7.75
M60	7.5	11.375	600	7.75
M61	8.0	11.875	600	7.75
M62	8.5	12.375	600	7.75
M63	9.0	12.875	600	7.75

obtained from centroid depths of about 7.0 to 11.0 km and a fixed chamber volume of 300 km^3. The quality of the cubic fit can be judged from the value of $R^2 = 0.999000$, which is statistically significant (>99%). Note that the maximum value of R^2 can be 1.00000. We note that for the linear correlation coefficient (r) to be statistically meaningful (Verma et al. 2005), it should be reported as rounded to at least three (in fact, four or more) decimal places, because the critical value tables for different significance levels have values with up to three decimal places (Ebdon 1988; Bevington and Robinson 2003). The R^2, therefore, will have to be reported to at least five (in fact, more) decimal places; otherwise, it may be indistinguishable from the maximum value of 1.

The values of the coefficients and the respective errors of the first term (without dc) and the three other terms (dc, dc^2, and dc^3) in Equation 1 are included. The statistically significant fit, quantitatively expressed in the R^2 parameter, is also indicated by relatively low errors of the coefficients in Equation 1. The values of the coefficients (−498.9, 49.76, and −1.653, respectively, for cd, dc^2, and dc^3; respective errors of 32.6, 3.66, and 0.135, equivalent to about 6.5%, 7.3%, and 8.2%, respectively) indicate the sensitivity of the dc variable. Similarly statistically valid results were obtained for the other equations (Equations 2 to 7; see R^2 values of 0.998990 to 0.998993). Note that had we reported rounded R^2 values to less number of decimal places, most of them will be indistinguishable from each other and from the maximum value of 1. The differences among the errors of the coefficients in Equations 1 to 7 could not then be explained from small differences in the R^2 quality parameter (Table 3).

Figure 2 Simplified geological models (M1, M5, and M9) of the Los Azufres geothermal field (LAGF), Michoacán, Mexico. These models were input in the three-dimensional simulator TCHEMSYS. Numbers 1 to 4 are for geological strata (Table 1).

Equations 8 to 16 corresponding to the chamber volume (V) parameter are presented in Table 4. All equations represent statistically significant cubic fit, because R^2 values are relatively high (0.969720 to 0.991220; confidence levels of >99%). However, the values of the coefficients, particularly, for the V, V^2, and V^3 terms are much smaller than those for the respective dc terms (compare Equations 8 to 16 with 1 to 7). For example, in Equation 8 that represents the behavior of δT as a function of V, the coefficients for V, V^2, and V^3 are, respectively, 5.80×10^{-3}, 11.67×10^{-3}, and 7.69×10^{-3}, with respective errors of 0.90×10^{-3}, 2.05×10^{-3}, and 1.52×10^{-3}, equivalent to about 15.5%,

Figure 3 Simplified geological models (M55, M59, and M63) of the Los Azufres geothermal field (LAGF), Michoacán, Mexico. These models were input in the three-dimensional simulator TCHEMSYS. Numbers 1 to 4 are for geological strata (Table 1).

Figure 4 Temperature field distribution. Temperatures are reported as a function of the depth in km (vertical axis on the right side of the diagram) or as the number of control volumes (cvn; vertical axis at the left side of the diagram). The conditions of this model (M55; Table 2) are as follows: the top of the magma chamber at 5 km depth, chamber volume of 600 km^3, and emplacement time of the 100,000 years (δt of 500 years).
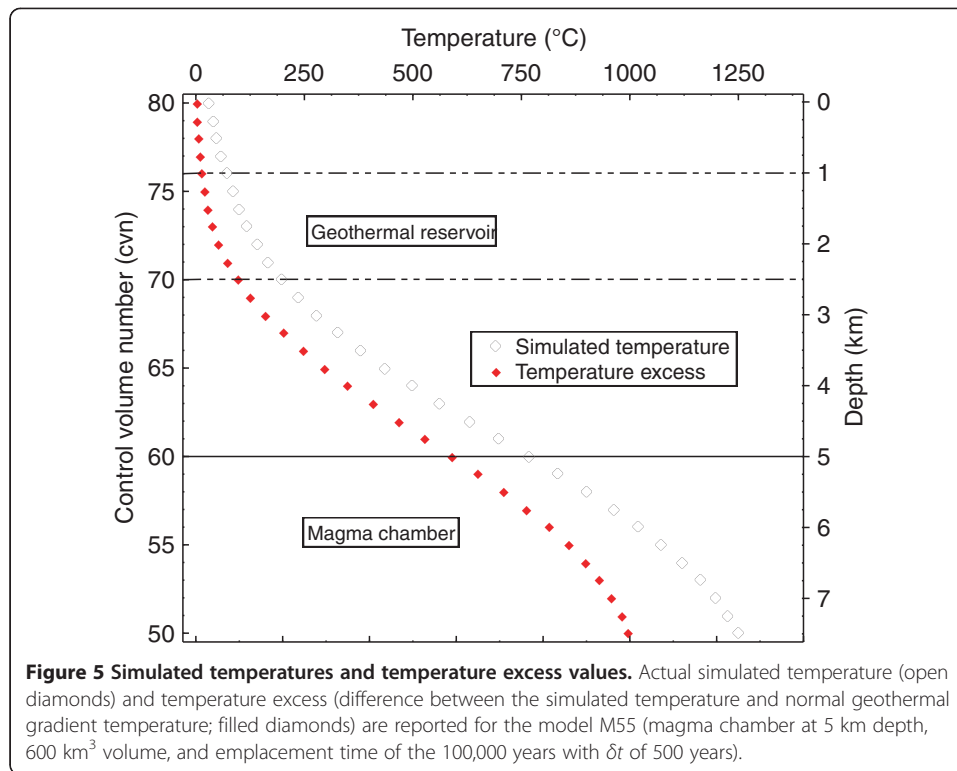
17.6%, and 19.7%, respectively. These mean values are much smaller than those for Equation 1, whereas the respective errors are much greater (15.5% to 19.7% for volume terms as compared to 6.5% to 8.2% for centroid depth terms). The same is true for all other equations of Tables 3 and 4. All these inferences are statistically valid as examined from significance tests through UDASYS software (Verma et al. 2013), which uses highly precise and accurate critical values (Cruz-Huicochea and Verma 2013; Verma and Cruz-Huicochea 2013). The errors of the coefficients of dc terms in Equations 1 to 7 vary from 6.5% to 8.2%, whereas those for the V terms in Equations 8 to 16 show the range of 15.5% to 27.8%. The intercept terms, on the other hand, show higher percent errors for dc (5.7% to 6.1%) than for V equations (0.004% to 0.3%).

The coefficients of the linear dc term in Equations 1 to 7 range from about −500 to −700, whereas those for the V term vary from about 7.0×10^{-3} to 5.8×10^{-3}. Similar relationship is valid for the quadratic and cubic terms (Tables 3 and 4). The relatively large values of the coefficients for the dc as compared to the V parameter imply that for thermal gradient, the magma chamber depth is much more sensitive than the chamber volume.

In order to confirm the importance of chamber depth as compared to its volume, we used the results of all 63 simulations to obtain the final best-fit equations (Equations 17 to 19; Table 5). Although the R^2 value for the cubic fit for the dc parameter is relatively high (0.691799), the errors for all coefficients are much higher than the respective coefficient values (Equation 17). Equation 18 representing the thermal gradient as a function of chamber volume seems to be statistically meaningless (note the almost negligible value 0.000000 of R^2 and extremely large errors for all coefficients).

Therefore, using all 63 simulations, we present our best-fit Equation 19 for the thermal gradient as a function of both parameters (dc and V). The R^2 value of 0.838748

Figure 5 Simulated temperatures and temperature excess values. Actual simulated temperature (open diamonds) and temperature excess (difference between the simulated temperature and normal geothermal gradient temperature; filled diamonds) are reported for the model M55 (magma chamber at 5 km depth, 600 km^3 volume, and emplacement time of the 100,000 years with δt of 500 years).

was obtained for this equation, which is not as high as for Equations 1 to 16. In Equation 19, the coefficients for the dc terms are consistently much higher than the respective coefficients for the *V* terms; for example, 169 for dc as compared to 0.069 for *V*, equivalent to a factor of about 2,400. The coefficients of quadratic and cubic terms are also higher for dc than for *V* (Table 5). The final combined equation, therefore, clearly confirms that the chamber depth is more sensitive than the volume. From the energy point of view, geoscientists (in particular geologists, volcanologists, and geophysicists) are encouraged to better constrain the chamber depth than its volume. This recommendation is valid not only for geothermal areas but also for active volcanoes. We also note that although we have evaluated the thermal regime in terms of the centroid depth, the inference will not change had we used the top of the chamber depth, instead of the centroid depth.

Preliminary three-dimensional thermal runs for a model of the Los Azufres geothermal field (LAGF)

The main aim of simulating these six additional runs for the model M55; Table 2) was to assess the effects of discretization time and mesh size (Figure 6). Their influence was evaluated at three different locations (L1, L2, and L3; Figure 4). For the largest discretization time of 20 years, the geothermal reservoir showed simulated temperatures of about 160°C for mesh size of 0.20 km and 175°C for mesh size of 0.10 km, whereas for 1 year, these temperatures were about 155°C and 160°C, respectively. Even larger differences in simulated temperature were observed for the other two locations (see L2 and L3 in Figure 6). Thus, both parameters - discretization time and mesh size - exert

Table 3 Cubic best-fit equations for the simulated thermal gradient in the geothermal reservoir as a function of the depth of the centroid of the magma chamber

Equation #	Depth of the top of magma chamber d (km)	Centroid of the magma chamber dc (km) [Model #]	Volume of the magma chamber V (km^3)	R^2	Equation[a]
1	5.0 to 9.0	7.0 to 11.0 [M1 to M9]	300	0.999000	$\delta T = (1668 \pm 96) - (498.9 \pm 32.6)\ dc + (49.76 \pm 3.66) \times dc^2 - (1.653 \pm 0.135)\ dc^3$
2	5.0 to 9.0	7.25 to 11.25 [M10 to M18]	350	0.998993	$\delta T = (1798 \pm 105) - (524.9 \pm 34.6)\ dc + (51.08 \pm 3.77)\ dc^2 - (1.656 \pm 0.136)\ dc^3$
3	5.0 to 9.0	7.5 to 11.5 [M19 to M27]	400	0.998991	$\delta T = (1933 \pm 114) - (551.1 \pm 36.5)\ dc + (52.35 \pm 3.88)\ dc^2 - (1.657 \pm 0.136)\ dc^3$
4	5.0 to 9.0	7.875 to 11.875 [M28 to M36]	450	0.998990	$\delta T = (2148 \pm 128) - (591.1 \pm 39.5)\ dc + (54.22 \pm 4.04)\ dc^2 - (1.657 \pm 0.136)\ dc^3$
5	5.0 to 9.0	8.25 to 12.75 [M37 to M45]	500	0.998990	$\delta T = (2377 \pm 143) - (632.5 \pm 42.6)\ dc + (56.09 \pm 4.19)\ dc^2 - (1.657 \pm 0.136)\ dc^3$
6	5.0 to 9.0	8.5 to 12.5 [M46 to M54]	550	0.998990	$\delta T = (2539 \pm 154) - (661 \pm 45)\ dc + (57.33 \pm 4.29)\ dc^2 - (1.657 \pm 0.136)\ dc^3$
7	5.0 to 9.0	8.875 to 12.875 [M55 to M63]	600	0.998990	$\delta T = (2795 \pm 172) - (705 \pm 48)\ dc + (59.2 \pm 4.4)\ dc^2 - (1.657 \pm 0.136)\ dc^3$

[a]The coefficients and their errors in the equations are rounded values according to the flexible rules put forth by Verma (2005). For Model # see Table 2.

Table 4 Cubic best-fit equations for the simulated thermal gradient in the geothermal reservoir as a function of the volume of the magma chamber
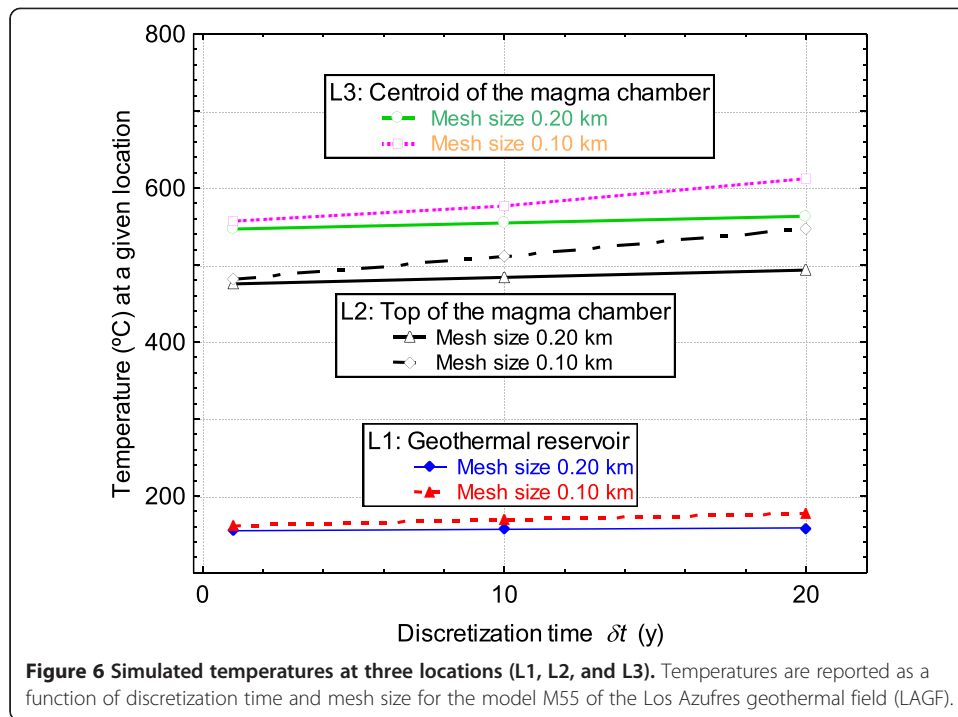
Equation #	Depth of the top of magma chamber (d, km)	Centroid of the magma chamber (dc, km)	Volume of the magma chamber (V, km³) [Model #]	R^2	Equation[a]
8	5.0	7.000 to 8.875	300 to 600 [M1, 10, 19, 28, 37, 46, 55]	0.991220	$\delta T = (45.712 \pm 0.129) + (5.80 \times 10^{-3} \pm 0.90 \times 10^{-3})\, V - (11.67 \times 10^{-3} \pm 2.05 \times 10^{-3})\, V^2 + (7.69 \times 10^{-3} \pm 1.52 \times 10^{-3})\, V^3$
9	5.5	7.500 to 9.375	300 to 600 [M2, 11, 20, 29, 38, 47, 56]	0.988839	$\delta T = (26.113 \pm 0.044) + (1.87 \times 10^{-3} \pm 3.12 \times 10^{-4})\, V - (37.6 \times 10^{-4} \pm 7.1 \times 10^{-4})\, V^2 + (24.9 \times 10^{-4} \pm 5.2 \times 10^{-4})\, V^3$
10	6.0	8.000 to 9.875	300 to 600 [M3, 12, 21, 30, 39, 48, 57]	0.986291	$\delta T = (13.7530 \pm 0.0139) + (55.2 \times 10^{-5} \pm 9.8 \times 10^{-5})\, V - (11.14 \times 10^{-4} \pm 2.23 \times 10^{-4})\, V^2 + (7.42 \times 10^{-4} \pm 1.65 \times 10^{-4})\, V^3$
11	6.5	8.500 to 10.375	300 to 600 [M4, 13, 22, 31, 40, 49, 58]	0.983621	$\delta T = (6.69010 \pm 4.03 \times 10^{-3}) + (15.04 \times 10^{-5} \pm 2.83 \times 10^{-5})\, V - (30.5 \times 10^{-5} \pm 6.4 \times 10^{-5})\, V^2 + (20.4 \times 10^{-5} \pm 4.8 \times 10^{-5})\, V^3$
12	7.0	9.000 to 10.875	300 to 600 [M5, 14, 23, 32, 41, 50, 59]	0.980872	$\delta T = (3.00922 \pm 1.07 \times 10^{-3}) + (37.8 \times 10^{-6} \pm 7.5 \times 10^{-6})\, V - (7.70 \times 10^{-5} \pm 1.70 \times 10^{-5})\, V^2 + (5.15 \times 10^{-5} \pm 1.26 \times 10^{-5})\, V^3$
13	7.5	9.500 to 11.375	300 to 600 [M6, 15, 24, 33, 42, 51, 60]	0.978078	$\delta T = (1.252520 \pm 2.59 \times 10^{-4}) + (8.80 \times 10^{-6} \pm 1.82 \times 10^{-6})\, V - (17.96 \times 10^{-6} \pm 4.13 \times 10^{-6})\, V^2 + (12.06 \times 10^{-6} \pm 3.06 \times 10^{-6})\, V^3$
14	8.0	10.000 to 11.875	300 to 600 [M7, 16, 25, 34, 43, 52, 61]	0.975271	$\delta T = (0.172276 \pm 1.19 \times 10^{-5}) + (37.8 \times 10^{-8} \pm 8.4 \times 10^{-8})\, V - (7.75 \times 10^{-7} \pm 1.91 \times 10^{-7})\, V^2 + (5.22 \times 10^{-7} \pm 1.41 \times 10^{-7})\, V^3$
15	8.5	10.500 to 12.375	300 to 600 [M8, 17, 26, 35, 44, 53, 62]	0.972478	$\delta T = (0.172276 \pm 1.19 \times 10^{-5}) + (37.8 \times 10^{-8} \pm 8.4 \times 10^{-8})\, V - (7.75 \times 10^{-7} \pm 1.91 \times 10^{-7})\, V^2 + (5.22 \times 10^{-7} \pm 1.41 \times 10^{-7})\, V^3$
16	9.0	11.000 to 12.875	300 to 600 [M9, 18, 27, 36, 45, 54, 63]	0.969720	$\delta T = (0.05697113 \pm 2.28 \times 10^{-6}) + (69.8 \times 10^{-9} \pm 1.6 \times 10^{-8})\, V - (14.37 \times 10^{-8} \pm 3.64 \times 10^{-8})\, V^2 + (9.68 \times 10^{-8} \pm 2.69 \times 10^{-8})\, V^3$

[a]The coefficients and their errors in the equations are rounded values according to the flexible rules put forth by Verma (2005). For Model # see Table 2.

Table 5 Cubic best-fit equations for thermal gradient in the geothermal reservoir as a function of either chamber depth or volume, or both, from all 63 simulated models

Equation #	Depth of the top of magma chamber (d, km)	Centroid of the magma chamber (dc, km)	Volume of the magma chamber (V, km^3)	R^2	Equation[a]
17	5.0 to 9.0	7.000 to 12.875	———————————	0.691799	$\delta T = (299 \pm 289) - (50 \pm 89)\ dc + (2.0 \pm 9.1)\ dc^2 - (0.009 \pm 0.306)\ dc^3$
18	———————————	———————————	300 to 600	0.000000	$\delta T = (11 \pm 239) + (1 \pm 1680)\ V - (2 \pm 3820)\ V^2 + (1 \pm 2820)\ V^3$
19	5.0 to 9.0	7.000 to 12.875	300 to 600	0.838748	$\delta T = (677 \pm 238) - (169 \pm 68)\ dc + (13.9 \pm 7.0)\ dc^2 - (0.392 \pm 0.234)\ dc^3$ $- (0.069 \pm 0.69)\ V + (0.37 \pm 1.58)\ V^2 - (0.31 \pm 1.17)\ V^3$

[a]The coefficients and their errors in the equations are rounded values according to the flexible rules put forth by Verma (2005).

Figure 6 Simulated temperatures at three locations (L1, L2, and L3). Temperatures are reported as a function of discretization time and mesh size for the model M55 of the Los Azufres geothermal field (LAGF).

significant influence in the estimated temperatures. These results are consistent with those recently simulated by Verma and Gómez-Arias (2013b) for the LHGF and LPGF.

The simulated 'present-day' temperatures of about 160°C at the middle of the geothermal reservoir (for δt = 1 year and mesh size = 0.10 km) are generally consistent with the actually measured temperatures (generally 120°C to 250°C) in the LAGF (Verma and Andaverde 1996). The simulated runs for the LAGF can be improved in the future by incorporating all geological processes, such as magma evolution (fractional crystallization, assimilation, and magma mixing), convection in the magma chamber and geothermal reservoir, and heat generation from radioactive elements. Similarly, the smallest possible discretization time and mesh size will be used.

Conclusions

The first three-dimensional thermal simulation study carried out for the Los Azufres geothermal field (LAGF) provided 19 best-fit cubic equations from 63 simulations to understand the influence of the depth and volume of the underlying magma chamber. The coefficients of the centroid depth terms were much higher than those of the volume terms, implying that the centroid depth is much more sensitive than the chamber volume. The chamber depth should therefore be better constrained than the chamber volume, not only in geothermal areas but also in active volcanoes. Preliminary thermal modeling of the LAGF also shows that the present-day mean simulated temperatures in the geothermal reservoir are around 160°C.

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