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Optimal discretization time and mesh size in three-dimensional temperature field simulation in two Mexican geothermal fields

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ABSTRACT

The sensitivity of neither the discretization time nor the mesh size is yet known in thermal modeling of geothermal systems. We determined their effect and optimal values in three-dimensional modeling of a magma chamber in two Mexican geothermal fields (Los Humeros, Puebla and La Primavera, Jalisco). Our results indicate that the discretization time is much more sensitive for the modeled subsurface temperatures than the mesh size. Therefore, all simulations must be carried out with the smallest discretization time (≤10 years for geothermal fields), which would result in the largest number of time steps. The importance of the mesh size is better understood in terms of the resolution of neighboring wells in a geothermal area. Four 3-D runs were simulated in the La Primavera geothermal field, whose results generally agreed with the actually measured temperatures in geothermal wells.

1. Introduction

The importance of discretization time and mesh size is poorly understood in thermal modeling of magma chambers in geothermal fields. In Mexico, such simulation studies in two-dimensions (2-D; Verma et al., 1990; Verma and Rodríguez-González, 1997), and three-dimensions (3-D; Verma and Andaverde, 2007; Verma et al., 2011, 2012; Verma and Gómez-Arias, 2013a) were based on discretization time of 1000 years (y) and homogeneous mesh size of 0.25 or 0.50 km for solving the heat transfer equation.

In other countries, such simulation studies have been focused on the thermodynamic behavior of geothermal reservoirs under exploitation and the estimation of their useful life time. The numerical models varied from 2-D (mesh size of about 0.10–0.25 km horizontally and 0.10–0.50 km vertically; Norton and Hulen, 2001; Yasukawa et al., 2003; McKenna and Blackwell, 2004) to 3-D (non-uniform mesh size of about 0.05–8.00 km horizontally and 0.02–2.00 km vertically; Stimac et al., 2001; Bataillé et al., 2006; Porras et al., 2007; Vedova et al., 2007; Romagnoli et al., 2010; Noorollahi and Itoi, 2011).

The discretization time was reported by Verma et al. (1990) as 1000 years (y) for modeling during 0.5 m.y. (500 time steps) in an area of 30 km × 20 km in the Los Humeros geothermal field, Puebla, Mexico; by Verma and Rodríguez-González (1997) as 1000 y for modeling during 0.24 m.y. (240 time steps) in an area of 24 km × 15 km in the La Primavera geothermal field, Jalisco, Mexico; by McKenna and Blackwell (2004) as 2500 y for modeling during 32 m.y. (12,800 time steps) in an area of 23 km × 9 km of the Basin and Range province (USA); by Bataillé et al. (2006) as 3 days for modeling (total modeled time was not clearly reported, but assuming it to be 20 y from their diagrams, about 2434 time steps) in a very small region of about 2.5 km × 0.6 km × 2.5 km of the Soultz-sous-Forêts, France; and by Porras et al. (2007) as 1 y for modeling during 1 m.y. (1,000,000 time steps) in about 13.8 km × 9.4 km × 3.0 km of the Momotombo geothermal field, Nicaragua. Verma and Andaverde (2007) and Verma et al. (2011) used 1000 y (500 time steps) for their 3-D simulations in the Los Humeros geothermal field, whereas Verma et al. (2012) employed 250 y (960 time steps) for simulation in the La Primavera geothermal field.

The mesh size information was also provided by some workers. Thus, Verma et al. (1990) in their 2-D modeling used mesh size of 0.50 km × 0.50 km, with total number of elements about 2400; Verma and Rodríguez-González (1997) used mesh size of 0.25 km × 0.25 km, with total number of elements about 5760; McKenna and Blackwell (2004) used mesh size of 0.23 km × 0.20 km and 0.13 km × 0.10 km, with total number of elements about 7470. Bataillé et al. (2006) in 3-D modeling employed a set of equidistant grid points of 128 × 64 × 128, with the total number of elements about 1,048,576. Porras et al. (2007) used nine horizontal layers ranging in thickness between 0.15 km and 1 km, with each layer having 207 grid blocks and the total number of elements

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as 1656. Vedova et al. (2007), on the other hand, used mesh size of 1.0 km × 1.0 km × 0.3 km, with total number of elements about 36,400. Verma and Andaverde (2007), Verma et al. (2011, 2012) and Verma and Gómez-Arias (2013a) used control volumes of 0.25 km × 0.25 km × 0.25 km; the entire simulated region of 30 km × 30 km × 20 km had to be subdivided into 1,152,000 elements. Finally, Guerrero-Martínez and Verma (2013) modeled a region of 20 km × 30 km × 20 km and used control volumes of 0.25 km × 0.25 km × 0.05 km, with the resulting 6,307,200 elements.

Thus, because neither the discretization time nor the mesh size was varied in any of the modeling studies, the effects of these two variables (discretization time and mesh size) on the solution of heat transfer equation is still poorly understood. This information is vital for a better understanding of the thermal regime and useful life time of a geothermal system, because such effects should be minimal if we were to consider the final solution of the heat transfer equation as reliable.

Therefore, our main objective in this work was to determine the optimal discretization time and mesh size, for which the conductive heat transfer equation was solved by the control volume method. We used eight different discretization times of 1000 y, 500 y, 250 y, 50 y, 20 y, 10 y, 5 y, and 1 y, and three mesh sizes of 0.50 km, 0.25 km, and 0.20 km. We applied the methodology to two geothermal fields in Mexico: Los Humeros, Puebla, and La Primavera, Jalisco. This provided us a very important result that the discretization time is much more important for temperature field simulation than the mesh size. Therefore, the least possible discretization time, such as <20 y (or equivalently >12,000 or 25,000 time steps), i.e., 10–1 y, or equivalently 24,000–500,000 time steps, should be used in all routine 3-D simulation work, in which a large total time, such as several hundreds of thousand years, could be required. Obviously, a smaller total simulation time would facilitate the use of a smaller discretization time. In such modeling of a wide region, several km on each side, a smaller mesh size, such as 0.20 km or less, is important for better resolving the somewhat different thermal regimes of neighboring wells.

2. Geological synthesis

2.1. Los Humeros geothermal field (LHGF)

The LHGF is located in the State of Puebla, close to the limits of the State of Veracruz, at the eastern part of the Mexican Volcanic Belt (MVB; Fig. 1) and, as the third important geothermal field of Mexico, it generates electricity from hot fluids extracted from the geothermal reservoir (Ferriz, 1985; Cedillo-Rodríguez, 2000; Verma et al., 2011). The geology of this field was described recently by Verma et al. (2011). The LHGF, at an average elevation of 2806 m above sea level, is located in an East–West valley. The Los Humeros caldera originated as a result of a voluminous (115 km^3) eruption of rhyolitic magma of Xáltipan ignimbrite at about 0.46 Ma (Ferriz and Mahood, 1984, 1987; Ferriz, 1985). The geology of the LHGF has been documented by several workers (e.g., Pérez-Reynoso, 1979; Verma and Lopez, 1982; Ferriz and Mahood, 1984, 1987; Ferriz, 1985; Verma, 1985, 2000; Verma et al., 1990; Andaverde et al., 1993). A geological synthesis of the LHGF was recently used by Verma et al. (2011) for 3-D thermal modeling during the entire eruptive history of this field (Fig. 2).

2.2. La Primavera geothermal field (LPGF)

The LPGF is situated in the western part of the MVB near the triple junction of three rifts or graben systems, namely, Tepic-Zacolaco rift, Colima rift, and Chapala rift (Fig. 1). The geology of the LPGF (about 13 km diameter, Fig. 3) has been summarized by several researchers (e.g., Mahood, 1980, 1981a,b; Mahood and Drake, 1982; Mahood et al., 1983; Villa-Merlo et al., 1987; Michael, 1988; Alatorre-Zamora and Campos-Enríquez, 1991; Yokoyama and Mena, 1991; Maciel-Flores and Rosas-Elguera, 1992; Verma and Rodríguez-González, 1997; Campos-Enríquez et al., 2005). Several eruptive events occurred at about 0.145–0.025 Ma (Mahood and Drake, 1982). The oldest units consist of granitic and granodioritic rocks below about 3000 m subsurface depth. This deeper layer is overlain by dominantly andesitic rocks about 1150 m thick. The third lithologic unit, about 100 m thick, consists of rhyolites. The upper unit is a sequence of lithic tuffs and minor andesites about 1750 m thick (Yokoyama and Mena, 1991; Verma and Rodríguez-González, 1997; Verma et al., 2012).

The LPGF is a very young (Late Pleistocene) volcanic complex in which the oldest pre-caldera lavas are about 65 m thick peralkaline rhyolites at about 400 m depth. The earliest eruptions of pre-caldera lavas took place between about 0.145 and 0.100 Ma. The eruption of 40 km^3 of Tala tuff at about 0.095 Ma represents the caldera-forming event. Tala tuff and caldera-lake sediments overlie these peralkaline rocks. Central domes and older ring domes (about 5 km^3) were also emplaced. Eruption of younger ring domes (about 3 km^3) took place at about 75 ka, which was followed by uplift and final eruption of southern arc lavas (about 7 km^3) at about 0.060–0.025 Ma (Fig. 3).

3. Conceptual models

In a geothermal field, it is reasonable to simulate a conceptual model of 30 km × 30 km horizontally (30 km in both north–south and east–west directions) and 20 km vertically (Table 1; Verma et al., 2011, 2012). For the primary heat source of the LHGF, we assumed a magma chamber of about 1400 km^3, whereas for the LPGF, a magma chamber of 500 km^3 was formulated (Verma, 1985). The top of the magma chamber was assumed to be at 5 km depth for both fields. Other conditions are summarized in Table 1.

For the LHGF, a simplified four-layer geological model (20 km from bottom to top, Fig. 4a; Verma et al., 2011) was assumed as follows: the deepest 17 km thick layer of intrusive igneous rocks; overlain by about 1 km thick limestone layer; 1 km of intermediate volcanic rocks; and the shallowest 1 km thick layer of acid volcanic rocks (tuff and ignimbrite). The thermo-physical properties of different rock types were taken from the actual laboratory measurements for rocks from the LHGF (Contreras et al., 1990). These properties are summarized in Table 2.

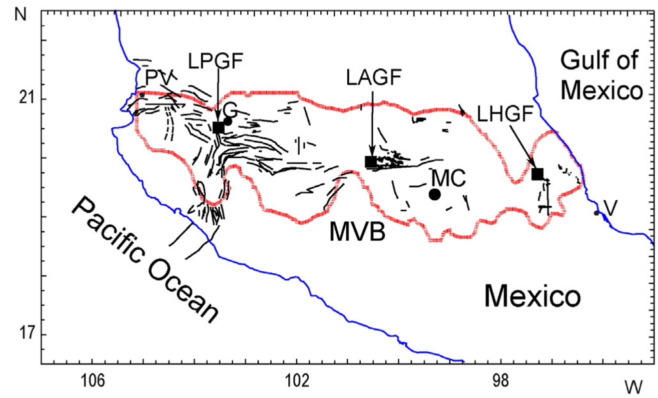

Fig. 1. Location of the Los Humeros geothermal field (LHGF), Puebla, in the eastern part of the Mexican Volcanic Belt (19°30′–19°50′ N latitude, 97°20′–97°35′ W longitude) and the La Primavera geothermal field (LPGF), Jalisco, in the western part of the Mexican Volcanic Belt (20°00′–21°00′ N latitude, 103°15′–103°45′ W longitude). The map was modified from Verma (2009). The abbreviations are: MVB, Mexican Volcanic Belt; PV, Puerto Vallarta; G, Guadalajara; V, Veracruz; MC, Mexico City; LAGF, Los Azufres geothermal field.