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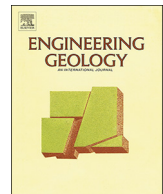
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Overexploitation of groundwater resources in the faulted basin of Querétaro, Mexico: A 3D deformation and stress analysis

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ABSTRACT

The City of Querétaro is located on a continental basin filled since the Oligocene with lacustrine and alluvial sediments, pyroclastic deposits, and interbedded fractured basalts. The graben structure of the basin was formed by two major North-South trending normal faults, among which the thicknesses of the filling materials vary many tens of meters in close distances. Hence, important differences of hydraulic and mechanical properties characterize the various geologic units. Groundwater has been strongly withdrawn over the last three decades in the study area, with a decline of the piezometric level exceeding 100 m. Because of the high variability of the geologic deposits, the piezometric decrease and consequently the effective stress increase are characterized by a large spatial variability. Piezometric variations are also due to faults that strongly impact on groundwater flow dynamics. The deformation and effective stress variability has caused large differential subsidence causing ground fracturing that has damaged the urban infrastructure of the City of Querétaro. This complex geological setting has been properly accounted into a three-dimensional (3D) flow and geomechanical modeling approach to quantify the displacement, deformation, and stress fields caused by water withdrawal. The static geologic model was accurately defined using geological logs from extraction wells, field mapping of faults, fractures, and the integration of major structures reported in previous geophysical works. The model has been calibrated using observed groundwater levels and land settlement records. The simulations have spanned the period from 1970 to 2011. The modeling results highlight that the areas where large differential subsidence and horizontal displacements developed correspond to the portions of the city where ground fractures are observed. Normal and shear components of the stress field changes accumulate along the discontinuity surfaces at depth, providing evidence that large piezometric declines can be a key factor triggering the fault reactivation. The spatial relationship between major withdrawals, discontinuities of the geologic structure, and accumulation of large stress and strain fields clearly emerged from the outcomes of the 3D geomechanical model.

1. Introduction

Cities in the central Trans-Mexican Volcanic Belt (TMVB) are example of zones where millions of people live, and the effects of climate change in terms of variation in the distribution and timing of precipitation have significantly threaten the availability of freshwater resources. Several cities, such as Mexico City, Aguascalientes, Morelia, and Querétaro, use groundwater as the primary source of water supply and contributes > 70% to the water needs of > 100 million inhabitants (Conagua, 2003; INEGI, 2011). Aquifer overexploitation has caused a significant decline of the piezometric head up to 100 m in these sites. The following consolidation of the sedimentary/volcanic basins has

caused land subsidence with rates on the order of 10 cm/yr associated with ground ruptures, the most documented case is Mexico City, where land subsidence may reach 40 cm/s (e.g. López-Quiroz et al., 2009; Cabral-Cano et al., 2008; Carreón-Freyre, 2010).

In Querétaro, the over-use of groundwater to provide water to the inhabitants of the valley has caused an alarmingly piezometric decline to about 120 m and, consequently, land subsidence. The cumulative pumping rate was quantified in 110 million m³/yr while the total recharge amounts to 70 million m³/yr (Carrera-Hernández et al., 2016). The aquifer is characterized by a highly heterogeneous geologic system, with sand-and-silt sediments intercalated with pyroclastic layers and fractured volcanic rocks. Because of the largely different geomechanical

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Fig. 1. Photographs showing some of the effects of differential land subsidence due to groundwater withdrawals in Querétaro: a) panoramic view of the 5 de Febrero Avenue (looking North), with the ground fracture displacements that have affected both the street and the bridge built originally horizontal between I and II; b) ground fractures have produced differential vertical displacements larger than 1.5 m; c) recent displacements (2016–2017) on 5 de Febrero avenue (looking south) along the trace of the Central Fault. The photographs were taken in the highest subsidence area defined by [Chaussard et al. \(2014\)](#).

properties of these materials and the presence of pre-existing buried faults ([Carreón-Freyre et al., 2005a, 2016](#)), land subsidence is accompanied by ground ruptures that damage the urban infrastructures of the City of Querétaro (Fig. 1).

An advanced three-dimensional (3D) finite element (FE) flow and geomechanical modeling approach is used in this work to investigate the relationships between the piezometric evolution due to groundwater pumping, land subsidence, and the complex geological system of the Querétaro Valley. The study is based on the consolidation theory by [Biot \(1941\)](#) and a 3D modeling approach is used. Indeed, only 3D models allow investigating the patterns of the vertical and horizontal components of the land displacements, the stress and strain fields at depth, and the possible generation of earth fissures and fault reactivation ([Gambolati and Teatini, 2015](#)). [Galloway et al. \(2008\)](#) observed that horizontal strains may be locally large near pumping wells where large hydraulic gradients developed, at locations where the aquifer system thins abruptly above inflections in the basement topography, and near the boundaries of hydrogeologic units with contrasting hydraulic and (or) mechanical properties.

Historically, horizontal strains (and displacements) in subsidence studies were ignored for various reasons. A main reason of a wider application of one-dimensional (1D) subsidence models (e.g., [Hoffmann et al., 2003](#); [Hung et al., 2012](#); [Mahmoudpour et al., 2016](#)) is because “many researchers argue that horizontal strains are much smaller than vertical strains in most subsidence investigations and can therefore be ignored” ([Galloway and Burbey, 2011](#)). Second, the paucity of regional horizontal-displacement measurements and the larger computation burden of 3D models have contributed to their limited use.

Usually, 3D geomechanical models were used to develop theoretical analyses (e.g., [Yang et al., 2015](#)) or to investigate the deformation field due to exploitation of groundwater resources at local scale. For example, [Burbey \(2006\)](#) used horizontal and vertical GPS measurements during a 60-day aquifer test to calibrate a 3D groundwater flow and deformation model with water-level measurements from the pumping well. A regional-scale investigation has been carried out by [Ye et al. \(2016\)](#). An explicitly coupled 3D groundwater flow and displacement model was developed for downtown Shanghai, China. The simulated horizontal displacements peak at about 10 mm, i.e. < 10% of the maximum land subsidence. The pseudo-tabular setting of the hydrogeologic units composing the sedimentary sequence beneath the Yangtze River delta and the scattered distribution of the pumping/re-charging wells were responsible for small and uniformly-distributed horizontal movements ([Ye et al., 2016](#)).

The geologic architecture of the Querétaro basin strongly differs from that of deltaic plains. For this reason, the three-dimensionality of the deformation and stress patterns caused by aquifer overexploitation is expected to be much larger in the study area. The models are calibrated using observed groundwater and land settlement records and then the 3D strain accumulations and stress changes compared with the distribution of the major ground ruptures mapped in the city.

A preliminary description of the model used in this study was published by [Ochoa-González et al. \(2013\)](#). The static/geologic model is kept from the previous work, but the modeling set-up is updated in relation to the boundary conditions, the parameter calibration, and the simulated time interval. A complete analysis of the 3D model outcome in terms of displacement, stress, and strain fields is presented and discussed here.

2. Geological setting

2.1. Structural geology

The Querétaro basin is a topographic depression filled by sediments formed by the normal displacement of regional faults since the Miocene ([Alaniz-Alvarez et al., 2001](#)) and volcanic activity. Two regional-scale fault systems cross the zone: 1) the N-S extensional fault system known as Taxco-San Miguel de Allende ([Alaniz-Alvarez et al., 2001](#)) and, 2) an E-W trending fault system, known as Chapala-Tula system ([Sutter et al., 2001](#)). The two systems divide the valley in a mosaic forming horsts, grabens, and half-grabens ([Xu et al., 2011](#)). The study area is located in the central depression of Querétaro City, formed by the interaction of the fault systems (Fig. 2). To the north, the central graben is delimited by two segments of an E-W trending south dipping normal fault with throws estimated at 200 to 400 m ([Carreón-Freyre et al., 2005b](#)). The E-W trending fault segments are cut by the N-S trending faults. To the south there is a normal fault inferred from the lineament of volcanic edifices such as the Cimatario volcano which is emplaced at the intersection with an N-S trending fault. The volcanic edifices play the role of watershed for the valley since the Miocene and controlled the deposition of the sediments filling the basin (< 5 Ma).

The central topographic depression is limited to the west by the N-S trending east dipping Balvanera fault for which a vertical throw of 150 m has been estimated ([Carreón-Freyre et al., 2005b](#)). The east boundary of the central depression is the N-S trending west dipping Cimatario fault characterized by a 60 m displacement. The asymmetry in the displacement of these graben flank faults is explained in terms of

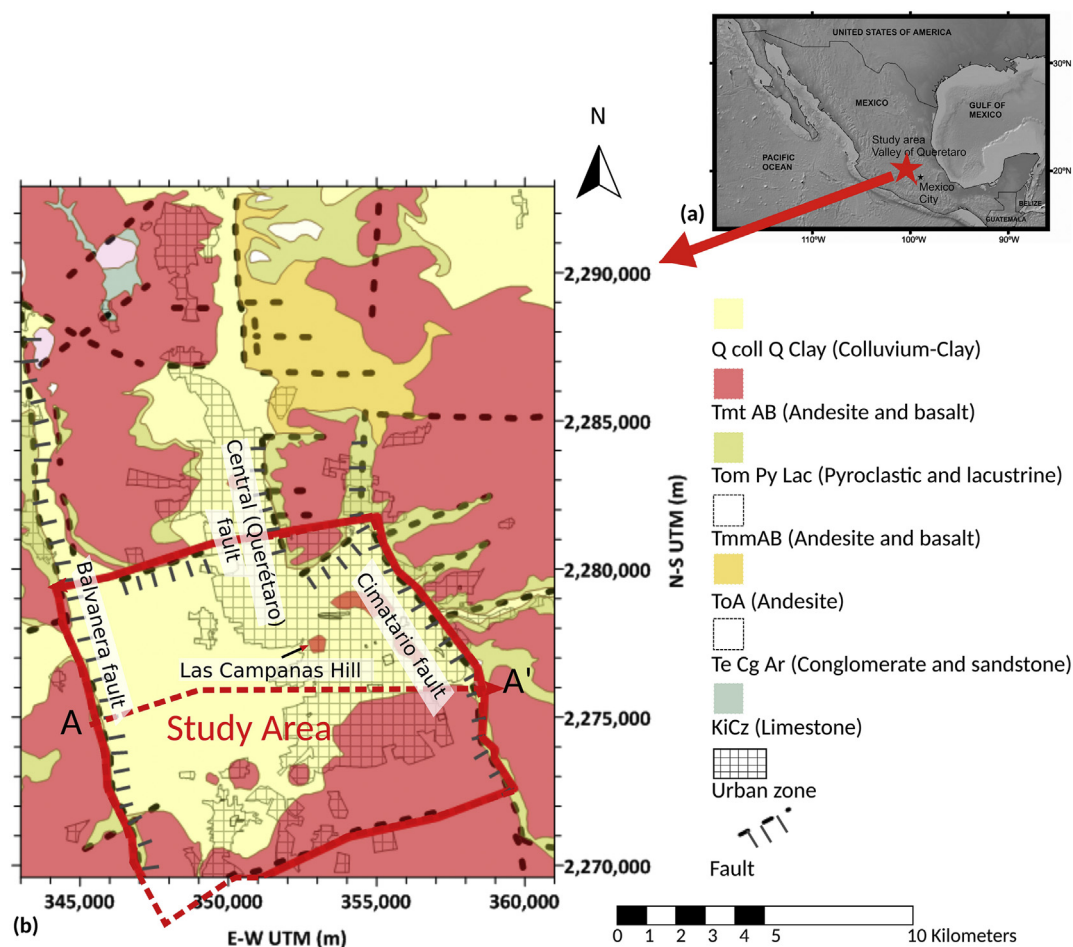


Fig. 2. (a) Location of the City of Querétaro in the Trans-Mexican Volcanic Belt. (b) Geological map of the Querétaro Valley, with the red line showing the simulation domain. The coordinate system is UTM 14N zone. Line A-A' represents the trace of the geological section shown in Fig. 3. Modified after Ochoa-González et al. (2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the presence of the N-S trending west dipping Querétaro Fault, which is hidden by the sedimentary cover in the study area. The Cimatario and Querétaro faults overlap in the central depression producing a relay ramp in the zone among them. Carreón-Freyre et al. (2016) documented vertical displacements for the buried Central Fault of 56, 70, and 90 m at the north, central, and south sectors of the area, respectively, through the correlation of the lava plateau in lithological logs located at both sides of the fault trace. Thus, the total vertical displacement accommodated by the Cimatario and Central faults is similar to the displacement in the Balvanera fault, bounding the basin westward, at least from the Miocene. There are several other minor buried faults, whose locations within the study area were identified by Pacheco et al. (2006) using gravimetric data measured transversally to the direction of the faults.

2.2. Stratigraphy

Six major geologic units compose the sedimentary-volcanic of the Querétaro Valley (Figs. 2 and 3). The volcanic are mainly fractured units and the sedimentary and pyroclastics rocks are mainly porous units. The surface Quaternary sequence is composed by lacustrine and/or colluvial deposits (Q Clay, Q Coll). The Cenozoic sequence includes a continental sedimentary unit with a predominance of conglomerates and sandstone (Tp Ar-Cg) below a predominantly volcanic rock sequence intercalated with thick pyroclastic and sedimentary deposits. The volcanic sequence comprises fissured basalts and lava flows from volcanoes (Tmt AB) with ages ranging from 12 to 5 My (Aguirre-Díaz

and López-Martínez, 2001) and basalts of the Oligocene to early Miocene (Tmm AB). In between, the pyroclastic and lacustrine sequences in Querétaro consist of different grain-sized deposits of 80 m thick (Tom Py-Lac), this unit includes the Ezequiel Montes Pumice, an important stratigraphic marker dated between 7.5 and 5.6 My (Aguirre-Díaz and López-Martínez, 2001). This pyroclastic and lacustrine sequence is the main hydrogeological unit exploited recently in the City of Querétaro (Carrera-Hernandez et al. 2016). A third Andesitic and Basaltic unit characterized by a smaller fracturing degree than Tmm AB (To AB or To A) is reported in some wells.

Therefore, the hydrostratigraphic units described downwards from the land surface are: 1) Q Clay: Quaternary lacustrine, surficial clays and low-permeable relatively thin deposits; 2) Tp Ar-Cg: sediments and volcanic rocks representing the main porous unit; 3) Tmt AB: Andesitic and Basaltic representing a highly fractured unit; 4) Tom Py-Lac: pyroclastic and lacustrine deposits forming the second main porous unit; 5) Tmm AB: older Andesitic and Basaltic fractured unit underlying Tom Py-Lac; 6) To AB Andesitic and Basaltic less fractured unit; 7) Hydrogeological basement, for modeling purposes it is assumed that a low permeability and rigid material bounds the compressible sequence from which groundwater is withdrawn even if other porous/fractured materials likely exist below To AB (Carreón-Freyre et al., 2005b).

2.3. Physical properties

According to the stratigraphic sequence, the “static” model accounted in the study is composed of an alternate sequence of granular

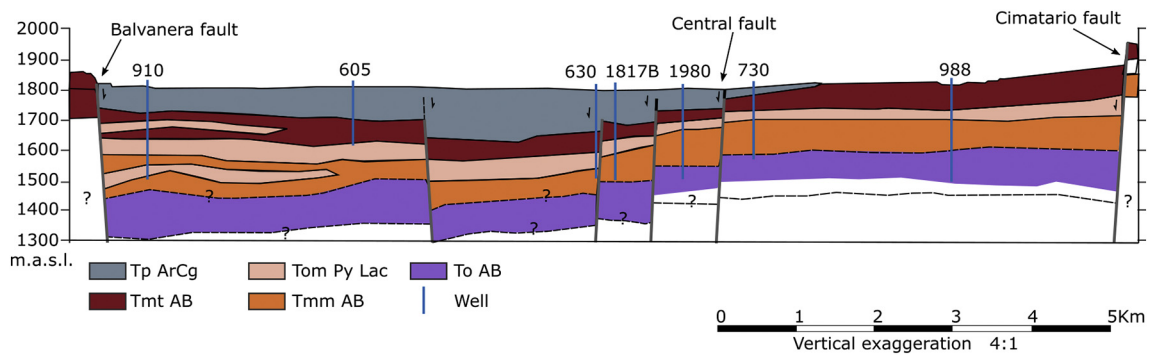


Fig. 3. West-east geological section A–A' (see Fig. 2b) obtained by the correlation of lithologic well logs and highlighting the vertical dislocation between the main stratigraphic units by normal faulting (modified after Carreón-Freyre et al., 2005b).

and fractured volcanic and sedimentary materials. Granular sequences include compressible fine grain-size materials such as clays, silts, fine sands, and volcanic ashes (pumice), interbedded with stiff permeable volcanic materials such as fractured basalts and andesites.

The compression indexes (C_c) of the Q Clay formation were determined according to the ASTM D2435 method (2011) in the Centro de Geociencias at UNAM. C_c values were transformed in oedometric bulk compressibility (c_M) through the relationship:

$$c_M = \frac{C_c}{2.3(1 + e)\sigma_v} \quad (1)$$

where $e = \frac{\varphi}{1 - \varphi}$ is the reference void ratio, φ the porosity, and σ_v the corresponding vertical effective stress. Fig. 4 shows the outcome of the two tests providing the minimum and maximum c_M values measured in the lacustrine materials. The range spans one order of magnitude, between 10^{-1} to 10^{-2} MPa $^{-1}$. The granular sequences Tp Ar-Cg are Tom Py-Lac are similarly composed by lacustrine, alluvial, and pyroclastic materials with variations in sedimentation sequence. The Tom Py-Lac sedimentary sequence was interrupted during the Oligocene by the

deposition of fall ashes (pyroclastic) that were easy altered to clays. Therefore, it can be assumed that Tom Py-Lac has a higher clay content than Q Clay and Tp Ar-Cg. Because of the impossibility of coring and testing in the laboratory intact samples from the deep Tom Py-Lac unit, its c_M has been assumed to be 30% larger than that measured for the shallower fine-grained materials. The compressibility values of rocks were taken from the literature (Zhang, 2017). As described in section 5.1, c_M has been the key parameter involved in the model calibration. The calibrated c_M values are summarized in Table 1.

Other physical properties of interest include: a medium porosity φ equal to 0.4 and 0.2 for the granular and the fractured volcanic materials respectively; specific gravity of soil solids $G_s = 2.4 \times 10^3$; Poisson ratio $\nu = 0.3$; and water volumetric compressibility $\beta = 4.6 \times 10^{-4}$ MPa $^{-1}$.

The hydraulic conductivity along the vertical (K_h) and horizontal (K_v) directions, reported by Carrera-Hernández et al. (2016) were used in the model, they established a stratigraphic sequence for the Querétaro Valley consistent with the presented in this study. The K_h and K_v values used in the flow model are summarized in Table 1.

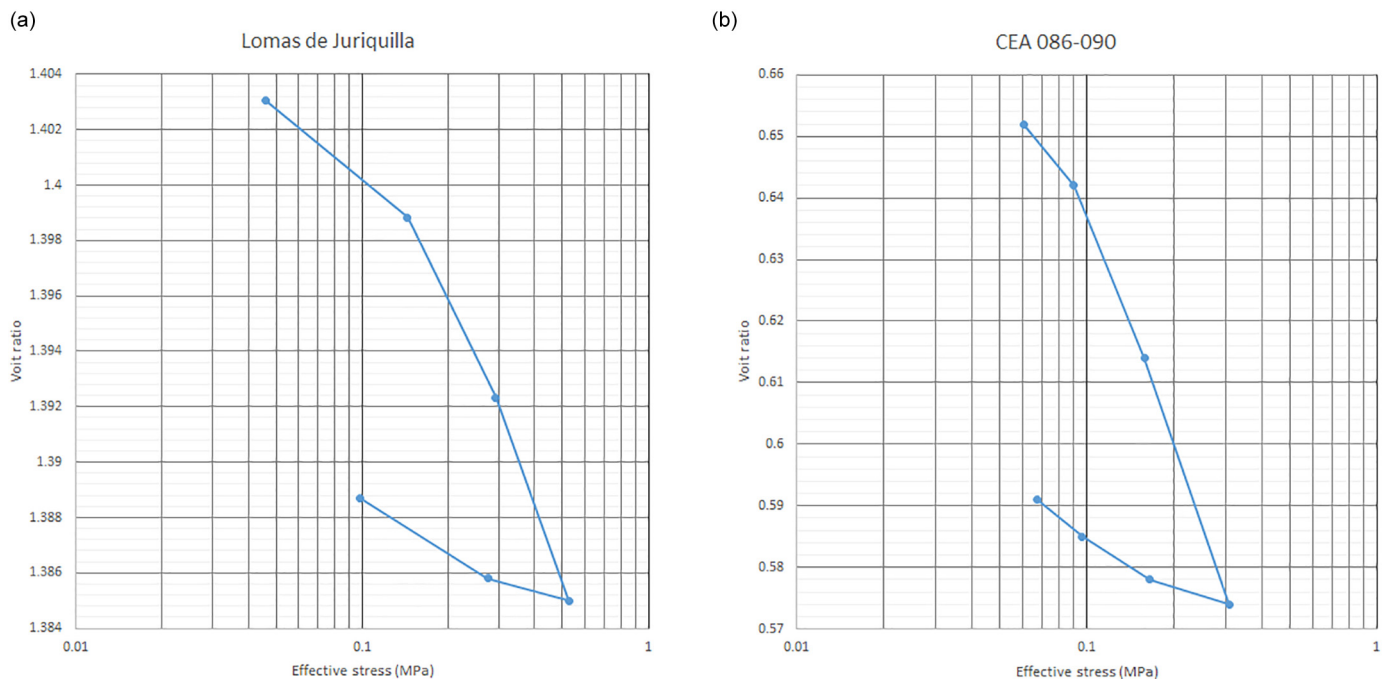


Fig. 4. Examples of oedometric test outcomes from two samples cored in the shallow Q Clay unit. These curves lead to the following values for the oedometric compressibility and specific storage: (a) $c_M = 1.13 \times 10^{-2}$ MPa $^{-1}$, $S_s = 1.1\text{E}-04$ m $^{-1}$ and (b) $c_M = 9.2 \times 10^{-2}$ MPa $^{-1}$, $S_s = 0.9\text{E}-04$ m $^{-1}$. The values represent the bounds of the variability range detected by the several oedometric tests carried out on samples cored from Q Clay. They have been obtained by extending the measured virgin section of the curve to an effective stress equal to 0.981 MPa, corresponding to a piezometric decline of 100 m, to derive a property value averaged over the stress range experienced by the porous medium because of the pressure decline.

Table 1

Hydraulic conductivity and calibrated geomechanical properties used in the model simulations.

Unit	K_h (m/day)	K_v (m/day)	c_M (MPa ⁻¹)	S_s (m ⁻¹)	E (MPa)	$c_M/c_{M,Qclay}$
Qclay	1.00	0.100	1.5×10^{-2}	1.5×10^{-4}	49	1
Tp Ar-Cg	1.00	0.100	1.5×10^{-2}	1.5×10^{-4}	49	1
Tmt AB	2.00	1.000	4.2×10^{-4}	5.0×10^{-6}	1786	0.03
Tom Py-Lac	0.10	0.010	2.0×10^{-2}	2.0×10^{-4}	37	1.34
Tmm AB	0.50	0.500	4.2×10^{-4}	5.0×10^{-6}	1786	0.03
To AB	0.06	0.006	2.1×10^{-4}	2.5×10^{-6}	3572	0.01
Base	0.01	0.010	2.0×10^{-6}	2.5×10^{-7}	364,371	0.0001

3. Hydrological evolution

3.1. Groundwater flow in faulted sequences

Groundwater flow in faulted aquifers has been characterized and modeled in the past using numerical models (Allen and Michel, 1999; Mayer et al., 2007). The presence of faults is simulated using different hydraulics properties relative to the surrounding materials, acting as a barrier (smaller permeability) or as a preferential flow-path (larger permeability), thus yielding a discontinuity in the piezometric levels between the two sides of a fault.

In Querétaro faulting strongly influence the groundwater system by compartmentalizing zones showing different piezometric values (Carreón-Freyre et al., 2005b). Previous numerical studies on the groundwater system (Ochoa-González et al., 2015; Carrera-Hernández et al., 2016) explicitly considered these faults and concluded that the truncation of the hydrostratigraphic units and the subsequent contrast of the hydraulic properties also contribute in the compartmentalization of the system.

3.2. Groundwater pumping and piezometric evolution

Groundwater withdrawal in Querétaro began during the early 1970s. According to the historical records of Conagua (2003), piezometric lowering occurred at an approximate rate of 3–5 m/yr. The piezometric level reached approximately 40 to 70 m below the land surface during the decade 1980–1990 when the shallow granular aquifer corresponding to Tmp Ar-Cg was exploited. From the 1990s to the 2000s, groundwater was pumped from the underlying Tmt AB volcanic unit. At that time, the average well depth varied between 150 and 200 m. The fractured aquifer was depleted over 2000–2010, and groundwater levels declined to the elevation of the second granular aquifer (Tom Py-Lac unit), i.e. between 80 and 120 m below the land surface.

The piezometric evolution versus time for some representative wells is provided in Fig. 5. Fig. 5a shows the well location and Fig. 5b the behavior of the drawdown from 1970 to 2012. Note that, because in Mexico the tube of water production wells is screened along its whole length, it is difficult to assign the recorded level to a specific aquifer. The majority of the wells are located along or near the faults and a few of them in the central part of the basin (Fig. 5a). The blue profiles in Fig. 5b are representative of the average piezometric behavior recorded in the Querétaro basin. The head drop measured in these wells was < 2 m/yr between 1970 and 1975 and grew to 3 m/yr afterward. Most of these wells are located to the West of the Central Fault, where ground ruptures are marked in Fig. 5a. In this area the Central Fault is believed to act as a boundary for the groundwater system and localizes the deformation associated with groundwater depletion (Carreón-Freyre et al., 2005b, 2016). A drawdown 5 to 10% smaller than the average was recorded for the wells colored in yellow in Fig. 5. Two of them (wells 0641 and 0641-A, close to each other) are located near a Tmt AB

outcrop, the Cimatario volcano, in the southern part of the study area. Other two piezometers (wells 1010 and 0870) are placed near the Central Fault, and another one (well 0722) on the Cimatario Fault along the eastern border of the model. Conversely, the wells marked in green and grey in Fig. 5 are characterized by a drawdown rate significantly smaller and larger, respectively, than the average behavior. The reasons of these persistent differences are comprehensively discussed in Ochoa-González et al. (2015).

4. Modeling subsoil deformation due to groundwater pumping

Ground ruptures due to groundwater withdrawal were reported in Querétaro City since 1986 and strongly damaged the urban infrastructures (Trejo-Moedano and Martínez-Baini, 1991; Carreón-Freyre et al., 2005a). Fracturing and fault reactivation were related with the differential displacements caused by the thicknesses variations of the compressible layers (Rojas et al., 2002).

4.1. Modeling approach

The 3D poro-elasticity equations originally developed by Biot (1941) provide the coupled flow and deformation fields caused by groundwater pumping from aquifer systems. In the explicitly-coupled formulation, which is usually implemented in regional long-term analyses (e.g., Teatini et al., 2006), the flow equation is solved for the pressure independently of the stress equation, with the gradient of the pressure variations later integrated into the equilibrium equation as a known external source of strength. This simplification hypothesis is fully warranted in large-scale problems (Gambolati and Teatini, 2015).

The classical groundwater flow equation governing the hydrodynamics in an aquifer system reads:

$$\nabla(K\nabla h) = S_s \frac{\partial h}{\partial t} + q \quad (2)$$

where h is the hydraulic head, K the hydraulic conductivity, t is time, q the source/sink, and S_s the specific elastic storage. Linear finite elements (tetrahedra) and a weighted finite difference scheme are used by the groundwater flow simulator FLOW3D (Teatini et al., 2006) to solve Eq. (2) in space and in time, respectively.

The variation in time and space of the hydraulic head dh provided by the solution of Eq. (2) is converted in incremental pressure $p = \gamma_w dh$, with γ_w the specific weight of water, and used as forcing factor in the geomechanical model to compute the 3D aquifer-system deformation. The equilibrium equations governing the deformation of a mechanically isotropic medium read (e.g., Verruijt, 1969):

$$G\nabla^2 u_i + (G + \lambda) \frac{\partial \varepsilon}{\partial i} = \frac{\partial p}{\partial i} \quad i = x, y, z \quad (3)$$

where u_i is the displacement component along the i -th coordinate direction, λ and G are the Lamé constant and the shear modulus of the porous medium, respectively, and ε is the volume strain. Finite elements using the same tetrahedral elements as the groundwater flow model are used in the SUB3D simulator (Teatini et al., 2006) to solve Eq. (3).

Well-known relations link the material properties in the flow and equilibrium equations (Teatini et al., 2006):

$$S_s = \gamma_w (c_M + \varphi\beta); \quad c_M = \frac{1}{\lambda + 2G} = \frac{(1 + \nu)(1 - 2\nu)}{E(1 - \nu)}; \quad G = \frac{E}{2(1 + \nu)} \quad (4)$$

with β the water volumetric compressibility, E the Young modulus, and ν the Poisson ratio. Explicitly coupling requires that c_M takes the same values in S_s and in the parameters E , λ , and G used in the geomechanical model. Notice that c_M is related to the compressibility index C_c provided by the usual graphical interpretation of oedometric tests through the relationship:

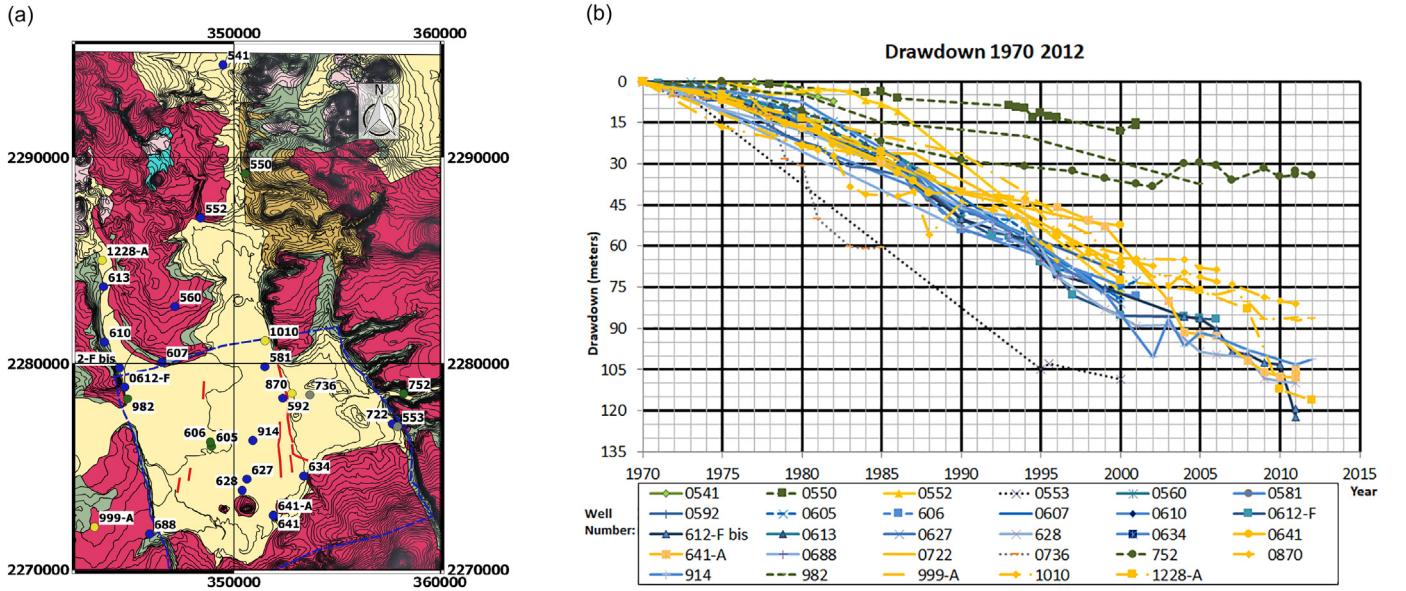


Fig. 5. (a) Geological map of the Querétaro Valley with the location of the monitoring wells. (b) Recorded drawdown from 1970 to 2012 in the wells of the Querétaro Valley. The colors of the piezometric profiles (blue, yellow, green, and grey) in (b) match those of the bullets used to mark to the corresponding well positions in (a). The blue lines and the red alignments in (a) represent the model boundaries and the trace of the ground ruptures, respectively. Modified after Ochoa-González et al. (2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$c_M = \frac{C_c}{2.3(1 + e)\sigma_v} \quad (5)$$

where $e = \frac{\varphi}{1 - \varphi}$ is the reference void ratio and σ_v' the corresponding vertical effective stress.

Explicit failure mechanics due to groundwater pumping, e.g. using appropriate formulation such as the Interface Elements (Franceschini et al., 2016; Ye et al., 2018), is not addressed in the numerical approach used in this paper. However, the complete strain ϵ and stress σ fields can be computed by the 3D displacement field as follows:

$$\begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_z \\ \epsilon_{xy} \\ \epsilon_{yz} \\ \epsilon_{zx} \end{bmatrix} = \begin{bmatrix} \partial/\partial x & 0 & 0 \\ 0 & \partial/\partial y & 0 \\ 0 & 0 & \partial/\partial z \\ 0.5\partial/\partial y & 0.5\partial/\partial x & 0 \\ 0 & 0.5\partial/\partial z & 0.5\partial/\partial y \\ 0.5\partial/\partial z & 0 & 0.5\partial/\partial x \end{bmatrix} \cdot \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zx} \end{bmatrix} = l \cdot \begin{bmatrix} 1 - \nu & \nu & \nu & 0 & 0 & 0 \\ \nu & 1 - \nu & \nu & 0 & 0 & 0 \\ \nu & \nu & 1 - \nu & 0 & 0 & 0 \\ 0 & 0 & 0 & (1 - 2\nu)/2 & 0 & 0 \\ 0 & 0 & 0 & 0 & (1 - 2\nu)/2 & 0 \\ 0 & 0 & 0 & 0 & 0 & (1 - 2\nu)/2 \end{bmatrix} \cdot \begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_z \\ \epsilon_{xy} \\ \epsilon_{yz} \\ \epsilon_{zx} \end{bmatrix} \quad (7)$$

with $\frac{E}{(1 + \nu)(1 - 2\nu)}$. The ruptures are more likely to develop and propagate where the tangential stress τ is relative large with respect to compression according for example to a Mohr-Coulomb failure criterion, and/or the normal stress component σ assumes negative/tensile values (Hernandez-Marin and Burbey, 2010).

4.2. 3D model set-up

The simulated domain is represented in Fig. 2, with boundaries

following the principal geological structures (faults). The area encompasses the oldest part of Querétaro urban zone and the surrounding suburbs and farmland.

The top surface of the 3D domain is represented by the land surface. The analysis of 46 well logs with different depths and 11 gravimetric profiles (Carreón-Freyre et al., 2005b; Pacheco et al., 2006) allowed deriving the architecture of the geologic units and the location of the discontinuities caused by faulting, including faults not mapped in the surface but inferred from indirect methods (Fig. 3). The upper part of the Base unit constitutes the bottom boundary of the model. The model represents accurately the distribution of the main seven geological units (see Section 2.2) that compose the sedimentary-volcanic basin. Fig. 6a shows a horizontal view of the 3D grid that is composed of 267,385 nodes and 1,520,244 tetrahedra. Fig. 7 shows a perspective view of the 3D simulated domain. A number of 1 to 10 finite element layers are used to discretize each geologic unit along the vertical direction.

The boundary conditions are specified as follows. In the flow model, fixed head (i.e., “water-source”) and no-flow conditions are prescribed along the lateral boundaries based on the geological setting (Fig. 6a), in particular the faults that can act as impermeable structures or water sources from larger depths, and the rocky outcrop distribution (Carreón-Freyre et al., 2005b; Ochoa-Gonzalez et al. 2015). The base-m is assumed impermeable, and a negligible (null) recharge/efflux is assumed on the land surface based on the climatic conditions of the area (the yearly average precipitation is < 100 mm and the maximum temperature ranges between 20 °C in winter and 30 °C in summer). Standard Dirichlet conditions are assumed in the geomechanical model. The basement is assumed to be fixed, the horizontal displacements of the outer boundaries are precluded, and the top surface is left free to move both vertically and horizontally. The model is solved in term of piezometric drawdown and displacements from 1970, which is assumed as a reference equilibrated state for both the groundwater flow and the geomechanical models (Fig. 5b).

The time interval spanned by the simulations cover a period of 41 years (14,965 days), i.e. from 1970 to 2011. Groundwater withdrawal is carried out through the group of 123 wells distributed in the area (Fig. 6a). The time behavior of the pumping rates is available for the main 21 wells. Concerning the remaining 102 wells, their withdrawal rates have been assessed using the existing values in the year

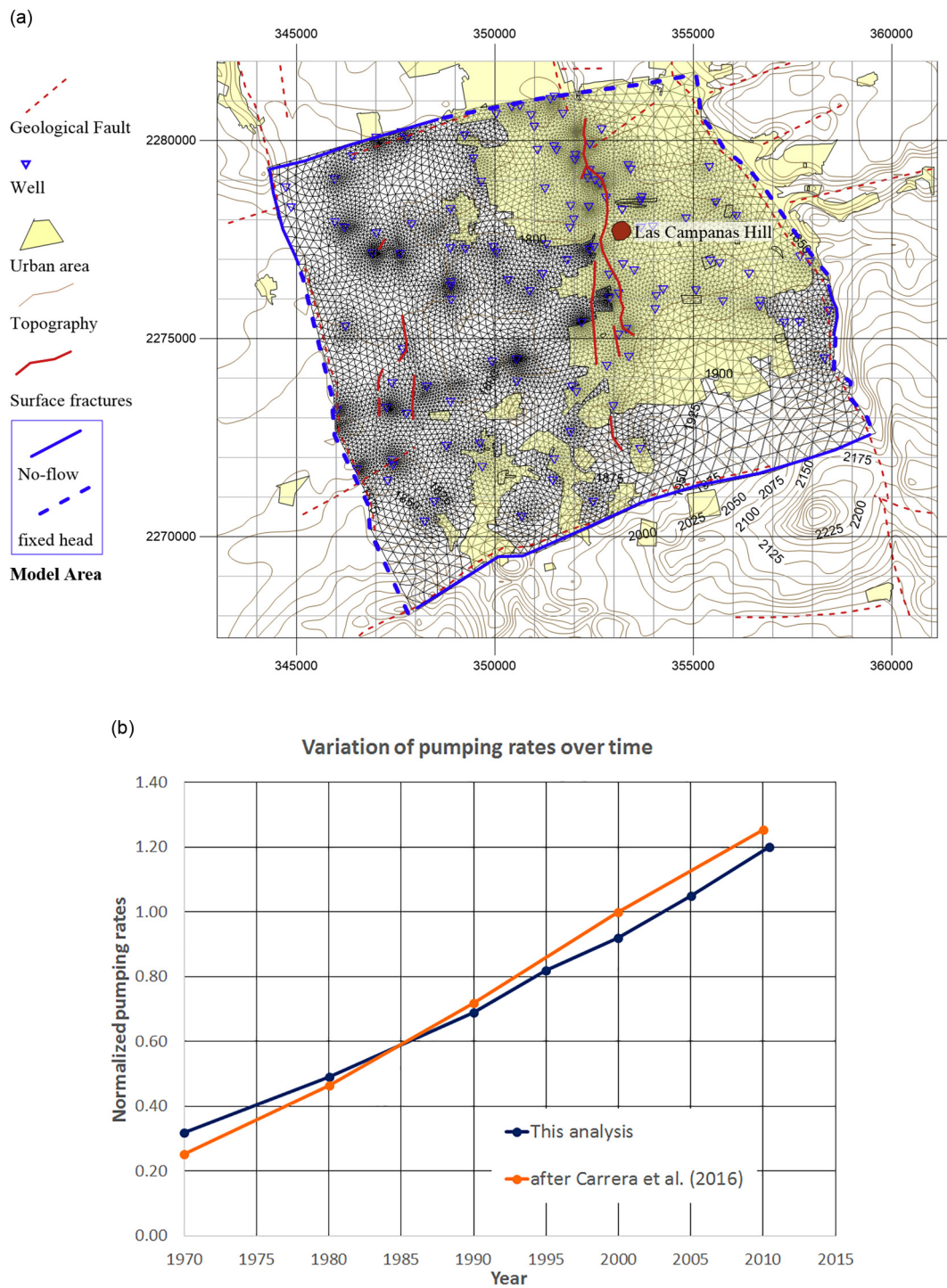


Fig. 6. (a) Horizontal projection of the 3D FE grid with the location of the main well fields. The blue lines correspond to major normal faults and are used to delimit the study area. The ground ruptures are represented by continuous red alignments and the topographic elevation by the brown curves. The boundary conditions for the flow model are indicated in the legend. (b) Comparison between the time behavior of the cumulative pumping rate normalized to the 2000 values as quantified in this study and used by Carrera-Hernández et al. (2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2000, with the temporal trend derived from the population growth in the City of Querétaro over the study period. The behavior vs time of the cumulative pumping rate obtained with this procedure is consistent with that reported in Carrera-Hernández et al. (2016) (Fig. 6b).

5. Modeling results

5.1. Model calibration

The groundwater flow and geomechanical models were initially calibrated using the available piezometric change and land subsidence records. Calibration by a trial-and-error procedure was focused on the soil compressibility c_M , while the hydraulic conductivity values

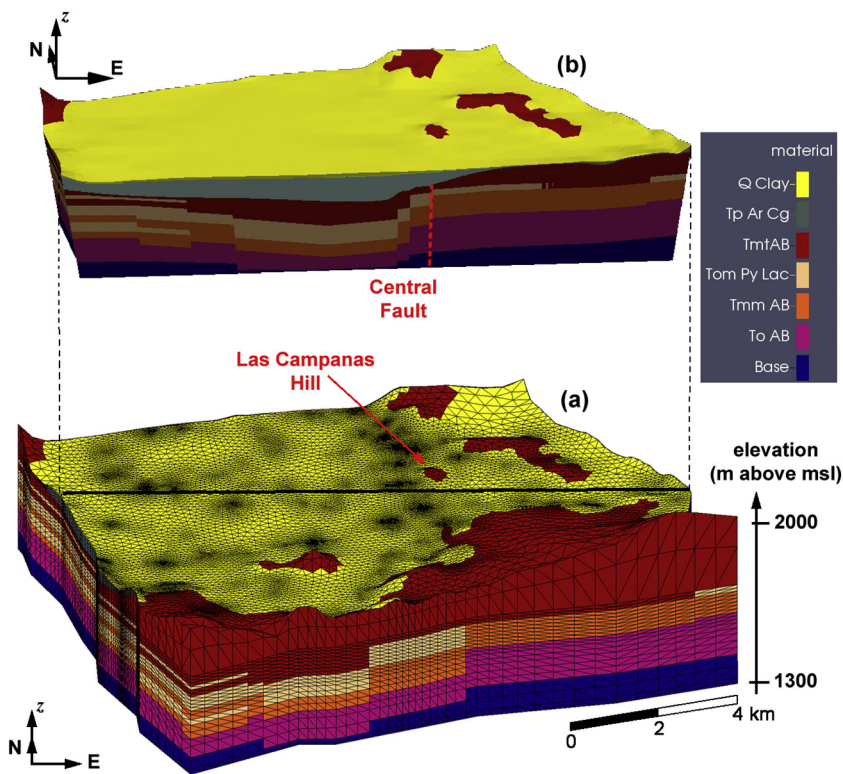


Fig. 7. (a) Perspective views of the 3D FE mesh used to carry out the flow and geomechanical simulations. (b) Vertical section of the 3D model domain along the black alignment shown in (a). The geologic units are highlighted by different colors. Note the graben-like structure between parallel normal faults and the largest Tp Ar-Cg thickness above the graben. Vertical exaggeration is 5.

previously calibrated by Carrera-Hernández et al. (2016) were used. Changes of c_M required to re-run the two models as it enters in the definition of both the specific storage (groundwater flow model) and Young modulus (geomechanical model), see Eq. (5).

The groundwater model was calibrated using the piezometric records provided in Fig. 5b and the maps of piezometric decline after Carreón-Freyre et al. (2005b). The piezometric evolution as computed by the model is shown in Fig. 8 where the maps of the head decline in

1980, 1990, 2007, and 2011 are presented. The decline peaked approximately 100 m in 2011, with a well-developed drawdown cone centered at 352'000 East and 2'278'000 North, UTM 14 N zone. Fig. 9 compares the measured and calculated drawdown versus time for one of the wells located in the critical area. The model fits satisfactorily the available measurements, particularly in relation to the main depletion cone located between 352'000–354'000 E-W and 2'276'000–2'280'000 N-S (dark red in Fig. 8). The largest drawdown

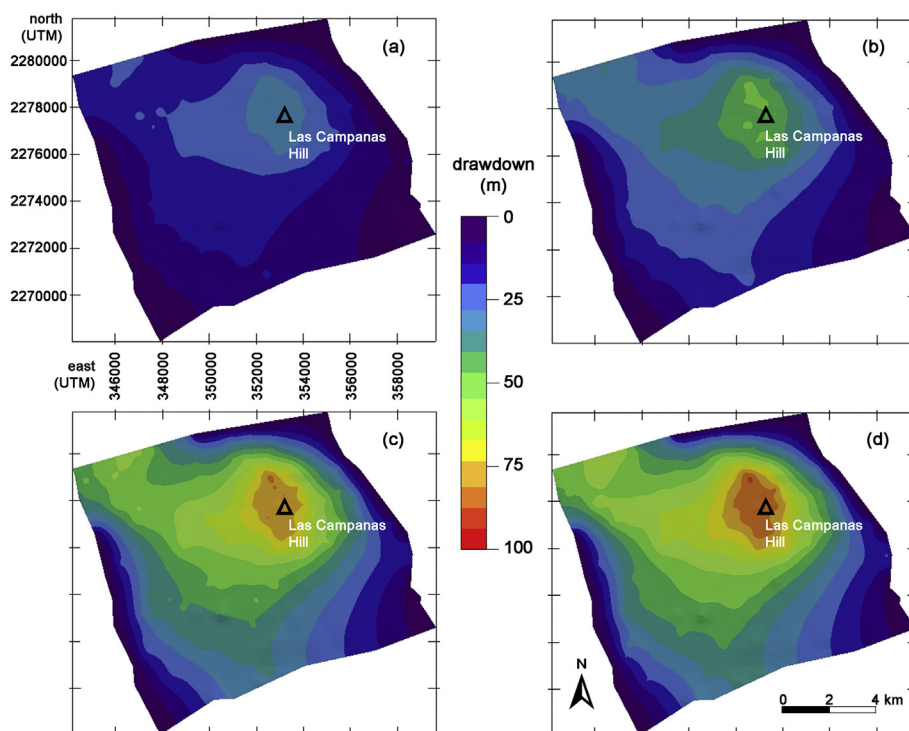


Fig. 8. Simulated piezometric drawdown from 1970 to (a) 1980 (10 years from the simulation inception), (b) 1990 (20 years), (c) 2007 (37 years), and (d) 2011 (41 years). The main depletion cone is located between 354,000–352,000 E-W and 2,278,000–2,276,000 N-S (dark red). The values refer to the shallowest layers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

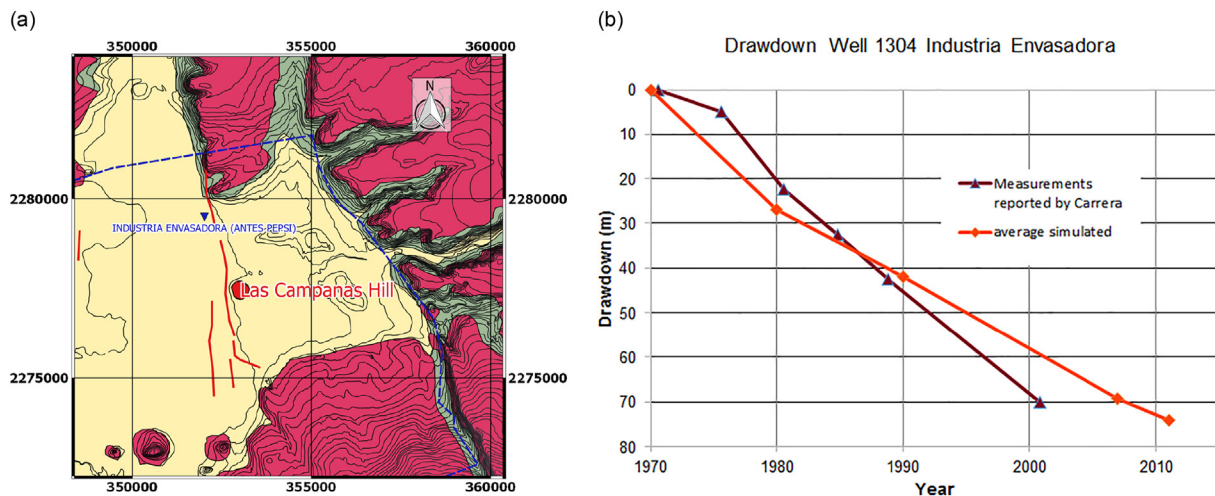


Fig. 9. Comparison between the computed and the measured drawdown at well No. 581. The location is provided in the map.

localized eastward of 352'000 E, in the east foot wall of the graben where the fractured units are located nearer to the land surface and the granular units are thinner.

Unfortunately, no long-term and extensive land subsidence records are available in the study area. The only available information has been obtained from [Chaussard et al. \(2014\)](#). They used SAR interferometry on a stack of ALOS images to quantify the average subsidence rates at the Querétaro Valley over the period from 2007 to 2011 ([Fig. 10a](#)). [Fig. 10b](#) shows the same amount as computed by the calibrated geomechanical model. To make the comparison straightforward, the u_x and u_z components of the simulated 3D displacement field were combined along the ALOS Line-of-Sight, which is characterized by an incident angle of 34.3° . The results match reasonably well the measurements, with a proper location of the main subsidence bowl and a maximum subsidence rate amounting to 4 to 5 cm/yr. In both the maps the subsidence extends mainly toward the western boundary of the simulated area.

[Table 1](#) summarizes the hydro-geomechanical parameters obtained from the calibration procedure. It is worth recalling that, because of the required consistency for the parameter values in the flow and geomechanical models, the calibrated c_M values allow the simultaneous match of the piezometric and subsidence measurements.

5.2. Outcome of the geomechanical model

The use of a 3D geomechanical model allows computing all the various components of the displacement, stress, and strain fields. In this section we provide a summary of relevant results on the land surface, on a plain at a specified depth, and along the vertical section shown in [Fig. 7](#).

[Fig. 11](#) shows the distribution of the land subsidence at 1980, 1990, 2007, and 2011. The maximum value amounted to approximately 2.8 m. The shape of the subsidence bowl differs from that of the piezometric decline ([Fig. 8](#)). These results provide evidence that land subsidence is not only related to the piezometric changes. The thickness and compressibility variability of the geologic units plays a major role. For example, the large drawdown close to the land surface within fractured volcanic rock (Tmt AB unit) in the surrounding of the Las Campanas Hill produced a relatively small land subsidence. This is because of the small specific elastic storage (yielding large drawdown) and deformability (yielding small land subsidence) of Tmt AB. Conversely, the thick granular sequences to the East of Central Fault (Tom Py-Lac and Tp Ar-Cg) mainly influence the geomechanical response of the system. The superposition of the ground rupture are with the computed subsidence maps shows that fractures developed where the maximum u_z gradient was computed.

The horizontal components u_x and u_y of the land displacement for

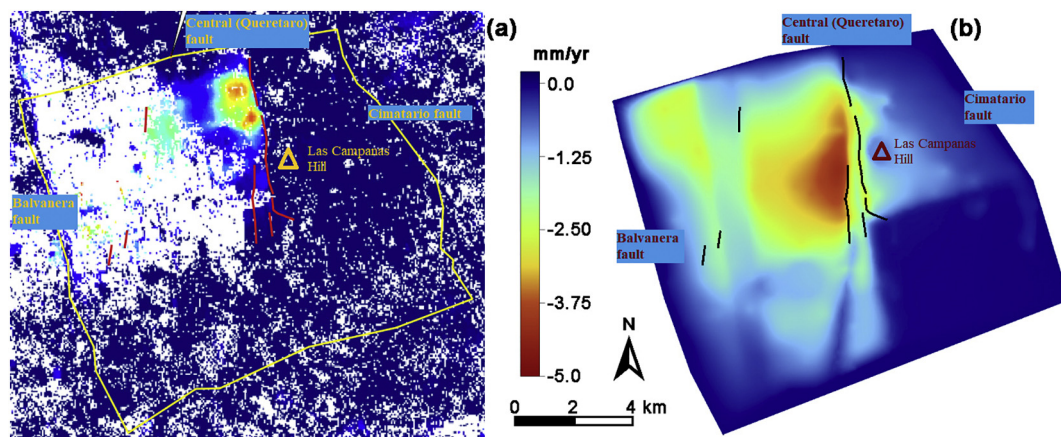


Fig. 10. Comparison between the average LoS displacement rate over the period between 2007 and 2011 (a) as measured by [Chaussard et al. \(2014\)](#) using SAR interferometry and (b) computed by the geomechanical model. Red (a) and black (b) lines correspond to mapped fractures in the study area, the yellow box in (a) represent the boundary of the simulated domain shown in (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

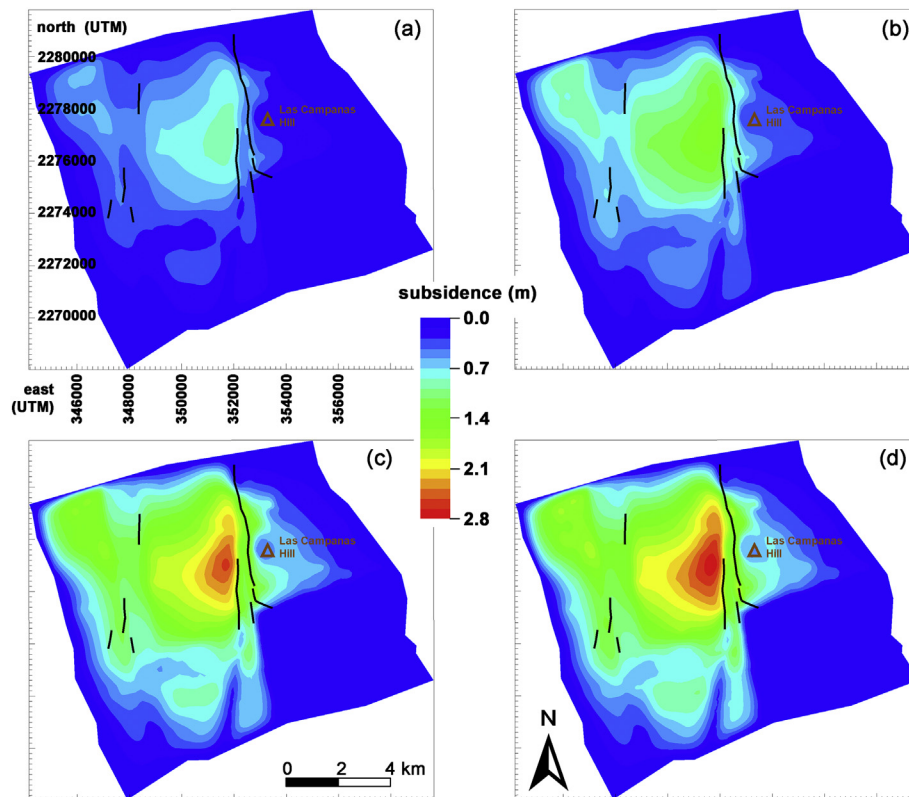


Fig. 11. Land subsidence as computed by the 3D geomechanical model in (a) 1980, (b) 1990, (c) 2007, and (d) 2011. The black alignments represent the trace of the observed ground fractures.

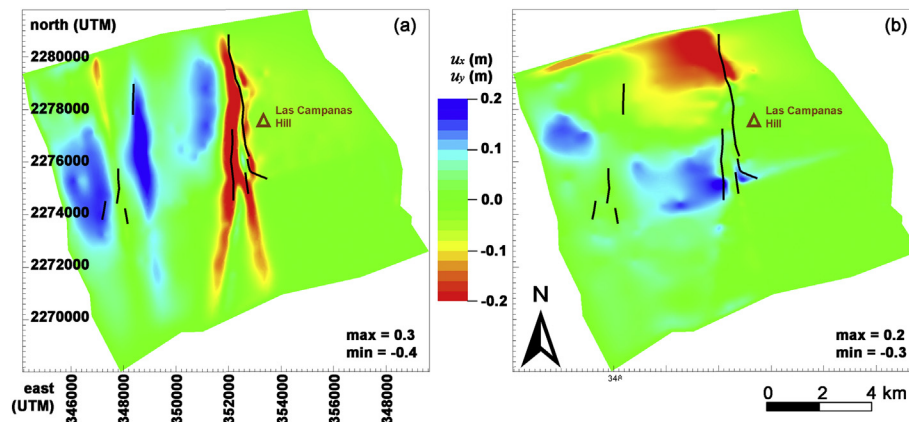


Fig. 12. (a) West-East u_x and (b) South-North u_y displacements as provided by the 3D geomechanical model at the land surface in 2011. The black alignments represent the trace of the observed ground fractures. Positive values mean eastward and northward movements in (a) and (b), respectively.

2011 are provided in Fig. 12. The two maps highlight the significant difference characterizing the pattern of the W-E and S-N displacements. The former are strongly influenced by the S-N geologic discontinuities, with the largest values assuming a band-shape located where the ground ruptures occurred. The latter develop in two large zones to the North and the South of the main subsiding bowl, with a smooth value distribution. Because of the lack of important geologic structures along the W-E direction, u_y is mainly controlled by the piezometric distribution, with movements toward the center of head drawdown.

Consistently with the available measurements (Fig. 10a), no displacement (both in the vertical and horizontal directions) takes place in the eastern portion of the study area because of the presence of the Cimataro Volcano system and the lack of compressible Tp Ar-Cg and Tom Py-Lac deposits (Fig. 7). Here a bifurcation and a slight change in direction were observed for the ground fractures (Fig. 11). The

maximum values of the horizontal displacements are almost one order of magnitude smaller than the maximum land subsidence; however, the largest u_x and u_y developed where u_z is less than half of the maximum value.

The components of the displacement field along the vertical section traced in Fig. 7 are presented in Fig. 13b to d. The geological section with the trace of the Central Fault is added in Fig. 13a to help with the result interpretation. The figures confirm that u_x and u_z patterns are strongly influenced by the graben structure and the heterogeneous distribution of the compressible and stiff units.

Figs. 14 and 15 show the model results in term of stress variation (with respect to the natural stress regime) at the end of the simulation period. Fig. 14 provides the normal stress in the W-E direction, σ_x , on the land surface and on the plain at 1700 m above msl, (approximately 150–200 m below the valley surface); that approximately corresponds

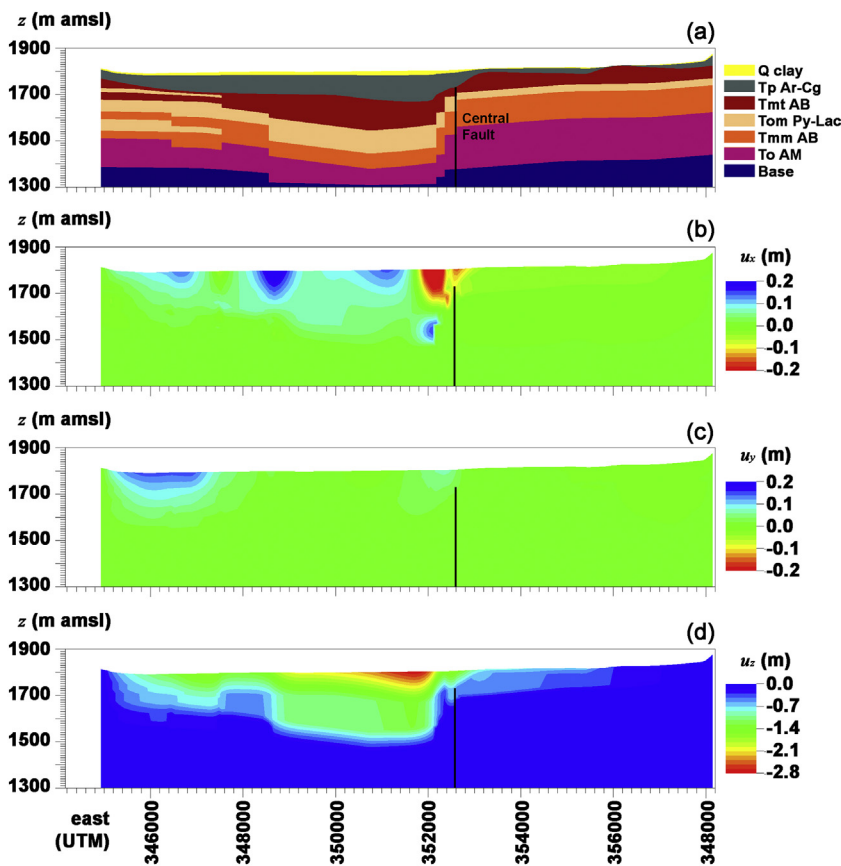


Fig. 13. (a) Geological model and (b) West-East, (c) South-North, and (d) vertical displacements as computed by the 3D geomechanical model in 2011 along the vertical section shown in Fig. 7. Positive values mean eastward, northward, and upward movements in (b), (c), and (d), respectively. The black line represents the trace of the Central Fault. The vertical exaggeration is 5.

to the boundary between the compressible To Ar-Cg and the stiff Tmt AB units. As expected, stress changes were negligible on the land surface because of the imposed traction-free condition. Conversely, large σ_x developed in depth, with an accumulation along the Central Fault. The distribution of the stress components σ_x , σ_z , and τ_{zy} along the analyzed vertical section (Fig. 7) is shown in Fig. 15. τ_{zy} , and secondarily σ_x , developed large values around the Central Fault and minor discontinuities on the western side of the graben. The horizontal stress accumulated within the stiff Tmt AB, which is overlain and underlain by the more compressible Tmt AB and Tom Py-Lac, respectively. The σ_z distribution is largely related to the pattern of the piezometric head decline. However, the geologic discontinuities strongly affect the σ_z pattern too.

Finally, Figs. 16 and 17 provide the model outcome in term of

normal strain on the land surface and along the selected vertical section, respectively, as of 2011. Large ($> 1\%$) stretching ϵ_x values developed along the trace of the observed ground ruptures (Fig. 16a) and at depth along the Central Fault (Fig. 17b). Consistently with the u_y pattern (Fig. 12b), the normal strain along the S-N direction ϵ_y was negligible (Fig. 16b). In relation to the normal strain along the vertical direction ϵ_z , its pattern on the top layer resembles more the piezometric drawdown (Fig. 8d) than land subsidence (Fig. 11d), with the exception where Tmt AB outcrops (Fig. 16c). Note for example the “red dot”, meaning zero deformation, corresponding to the Las Campanas Hill, in the center of the most compacting zone. Fig. 17c provides a clear picture of how deformation almost exclusively occurred in the granular units, which are approximately 2 orders of magnitude more compressible than the volcanic formations (Table 1). The vertical displacements

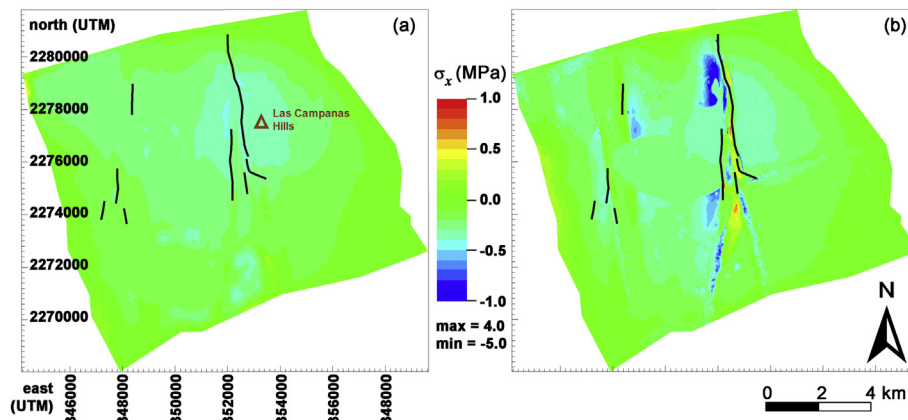


Fig. 14. West-East normal stress σ_x in 2011 as provided by the 3D geomechanical model at (a) the land surface and (b) an elevation of 1700 m above msl. Negative values mean compression, positive mean traction. The black alignments represent the trace of the observed ground fractures.

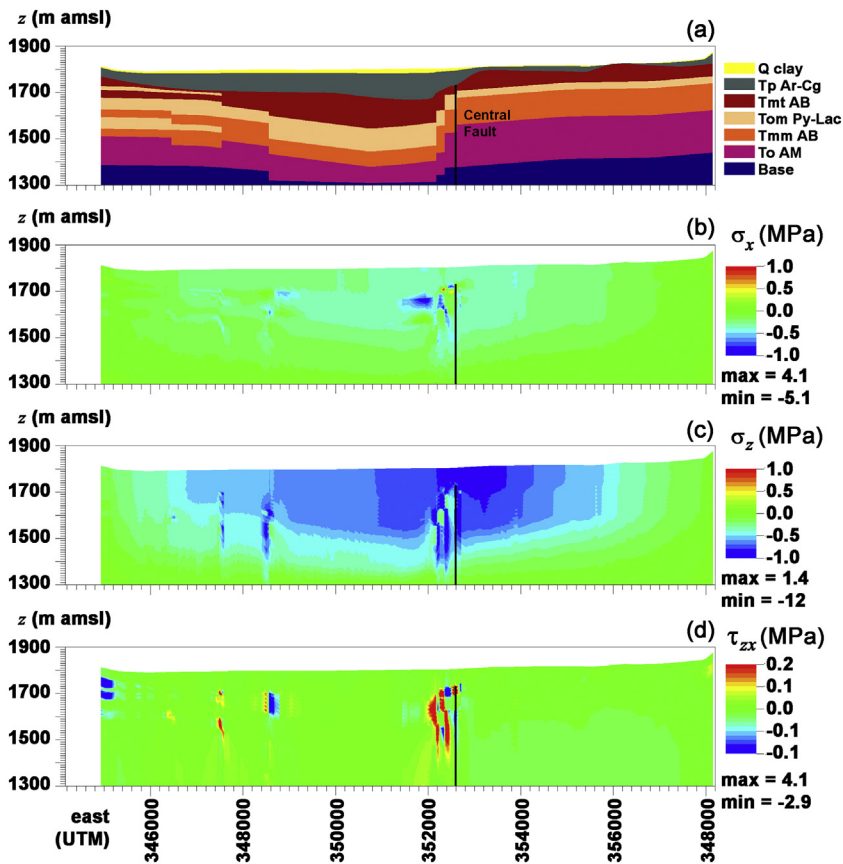


Fig. 15. (a) Geological model and (b) West-East normal stress σ_x , (c) vertical normal stress σ_z , and (d) tangential stress τ_{zx} as computed by the 3D geomechanical model in 2011 along the vertical section shown in Fig. 7. Negative values in (b) and (c) mean compression, positive traction. The black line represents the trace of the Central Fault. The vertical exaggeration is 5.

shown in Fig. 13d are the integral along z of the vertical strain (Fig. 17c) which depends on the drawdown and the compressibility of the geologic units. In the eastern part of the study area (Fig. 17c,

coordinate < 348'000 E, UTM 14 N zone), where the Tom Py-Lac unit is interbedded, there are a higher thickness of granular material (Fig. 17a) and the model shows a secondary subsidence bowl (Fig. 11).

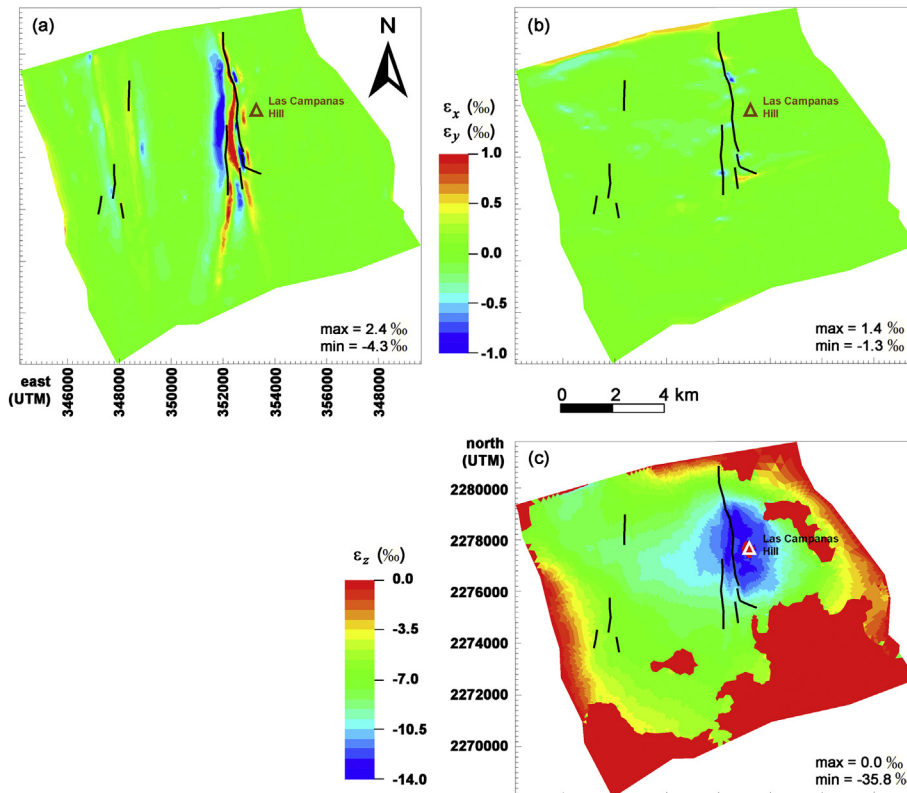


Fig. 16. (a) West-East, (b) South-North, and (c) vertical strain at the land surface in 2011. Blue (negative) colour represents squeezing. Red (positive) colour represents stretching in (a) and (b), or null strain in (c). The black alignments represent the trace of the observed ground fractures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

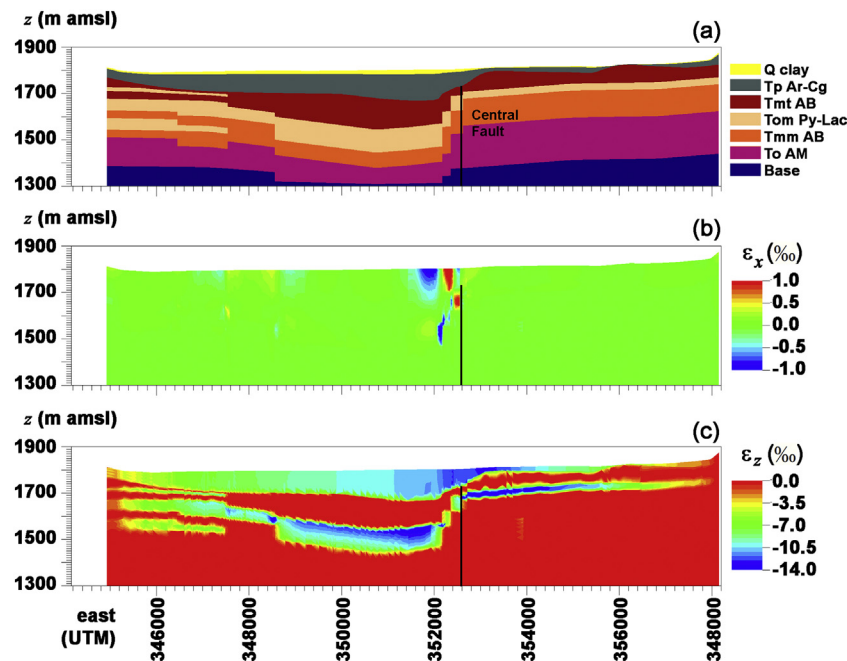


Fig. 17. (a) Geological model, (b) West-East strain, and (c) vertical strain as computed by the 3D geomechanical model in 2011 along the vertical section shown in Fig. 7. Negative values in (b) and (c) mean squeezing, positive stretching. The black line represents the trace of the Central Fault. The vertical exaggeration is 5.

6. Discussion

This paper presents a modeling investigation on the relationship between the heterogeneous distribution of the geomechanical properties and the differential deformation and stress fields in a subsiding basin, with specific reference to the Querétaro volcano-sedimentary sequences where extensive groundwater depletion is ongoing since the early 1970s. This is a complex issue that has not been addressed with detail in the literature.

The obtained results highlight the importance of using 3D geomechanical simulators when the subsiding basin is characterized by a complex geologic setting. One-dimensional modeling approaches properly describe deformation in the vertical direction and are appropriate to simulate granular multi-aquifer systems with a tabular setting. In Shanghai, for example, where the hydrogeological setting is characterized by flat clayey and sandy alluvial layers, Ye et al. (2016) showed that the main features of the deformation field are limited to the vertical direction. The use of 3D models is particularly appropriate to relate the localization of deformation with the stress fields. Our results show that thickness variations of fractured volcanic and granular units directly affect the pressure changes in the deep layers and the distribution of the displacement and deformation at the surface.

Moreover, Quaternary displacements on the N-S and E-W trending fault systems were proposed in the past (Alaniz-Alvarez et al., 2001; Zuñiga et al., 2003). Although there is not available information in their magnitude and timing, the Quaternary displacements in buried faults below the study area may have contributed to the presence of discontinuities and fractures in the sedimentary sequence. Differential compaction due to groundwater exploitation caused land subsidence in the hanging wall adjacent to the Central Fault (Chaussard et al., 2014) and vertical slip along the fractures traces producing a fault scarp. In the Central Fault the scarp formed by the vertical displacements reached up to 2 m in height over the last 30 years. The fractures and the regional extensional faults are characterized by the same geometry.

Displacements were examined in trench excavations at two sites confirming that in the surface the fault and associated fractures slipped previously within the last 25 ka, nevertheless it was assumed that most of the displacement was accommodated in the clayey layers (Carreón-

Freyre et al., 2016). This suggests that compaction of unconsolidated sediments resulting from water extraction enhanced the displacement in the Central Fault, where the vertical component of the displacement in the near surface strata is > 1.0 m. This amount is equivalent to the surface subsidence recorded during the last ~30 years.

Slip of the fault planes may have occurred not only at the surface but also at depth. Carreón-Freyre et al. (2016) have documented the sudden rupture of groundwater extraction wells along faults or stratigraphic contacts, at depths ranging from 70 to 150 m. The evidences suggest that at different depths the faults can be in a critical stress state and any perturbation of the system equilibrium, such as pore pressure depletion, may result in vertical and horizontal displacements of the discontinuities. Consistently with the results obtained for other faulted basins (e.g., Hernandez-Marin and Burbey, 2010), the modeling output confirms this possibility and suggests that the presence of geologic discontinuities has an important role in the localization of stress changes during aquifer exploitation (Fig. 15). Another effect of the long-term fault displacements is the juxtaposition of high compressibility materials (Tom Py-Lac) and stiffer layers (Tmt AB) in the direction perpendicular to the fault plane (Fig. 17).

Finally, the model outputs suggest that the areas most affected by land subsidence are not necessarily associated with the major withdrawn, as mentioned by Bell et al. (2002). Vertical sections of the displacement and strain fields (Figs. 13 and 17) allow for a better understanding of how groundwater depletion and hydrogeological setting combine in causing different subsidence amounts. Local piezometric and deformation measurements alone cannot suffice to explain the overall recorded subsidence.

7. Conclusions

Overexploitation of groundwater resources in faulted sedimentary-volcanic basins poses severe problems to the safety of structures and infrastructures located in urban areas. Large land subsidence may develop because of the presence of very compressible alluvial and pyroclastic materials and significant differential displacements may affect the land surface because of the heterogeneous distribution of granular compressible and fractured rocky deposits. Ground ruptures may easily

occur because of fault reactivation and stress and strain accumulation along discontinuity surfaces.

Geomechanical modeling of such occurrences cannot be effectively carried out adopting the 1D vertical approach traditionally used in land subsidence studies. In this work a complete 3D model is used to understand the geomechanical processes caused by groundwater pumping in one of these basins, specifically the Querétaro Basin in Mexico. Although based on a continuous approach, which is not capable to quantify fault and rupture opening and slippage, the proposed model gives us the possibility to provide a clear picture of the 3D displacement, stress, and strain fields caused by groundwater pumping.

The major outcomes can be summarized as follows:

- land subsidence is accompanied by significant horizontal displacements of the land surface. The horizontal movements orthogonal to the discontinuity planes concentrate precisely in correspondence of the fault trace, where ground ruptures are observed;
- both the normal and shear components of the stress field changes accumulate along the discontinuity surfaces at depth. This result provides evidence that large piezometric declines can be a key factor triggering the reactivation of faults;
- significant normal strains, in particular stretching, develop on the land surface above the faults where ground rupture are more likely to occur.

To the authors knowledge, this is the first modeling study that allows making such inferences in a real three-dimensional setting. The same modeling approach can be profitably used in the future to cast light to the geomechanical processes that are affecting several other basins similar to the Querétaro Basin in Central Mexico, Iraq, Pakistan, China, and South-western USA. Geomechanical modeling studies follow the damage occurrences and are usually used to plan possible mitigation strategies. Unfortunately, land subsidence and ground rupture cannot be recovered. Taking inspiration from the outcome assessed by this study, we hope that in the near future geomechanical models will also be used proactively, i.e. to develop effective plans of sustainable use of the groundwater resources to avoid the occurrence of subsidence and ground rupture hazards.

Acknowledgments

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