Structural control on the subsidence faults alignment in Irapuato - Mexico

Ramiro Rodríguez Castillo, Aarón Schroeder Aguirre

Abstract: The study area, Irapuato City, is located in the upper limits of the Transmexican Volcanic Belt, TVB, Central Mexico, where volcanic rock is predominant. Subsidence is affecting Irapuato urban area. Subsidence is affecting Irapuato urban area, evidenced by terrain fractures and subsidence faults and is associated to the intense abstraction regime of more than 1600 active wells, from which only 85 are controlled by municipal water authorities. There are not active tectonic faults in the area. Fifteen fault systems have been detected in Irapuato with a total length of 25 km. Subsidence velocity is 1.4 – 2.5 cm per year. Accumulated vertical displacements in 10 years ranges from 2.05-2.15 m. Faults were geo-referenced using a GPS total station, fault preferential orientation is North-East and all data were incorporated into a Geographic Information System (GIS). There is a structural control on fine material deposition and geometry and consequently in fault orientation. Fault orientation and distribution is controlled by the geometry of plastic sediments deposition mainly lacustrine and fluvial clay and lime. Shallow lacustrine sediments associated to a former lake defined two of the main fault systems. Subsidence faults were correlated with abstraction regime, the greatest urban supply volumes are extracted in the middle of the two main fault systems. Agricultural wells are located inside the urban area, its abstraction also contributed to subsidence displacements.

Keywords: subsidence faults, agricultural abstraction, Irapuato

Riassunto: *La subsidenza colpisce diverse città negli altopiani Messicani. L'abbassamento del terreno viene considerato un rischio naturale. Non c'è un fondo speciale per le popolazioni colpite poiché non viene considerata una calamità. Le carte del rischio basate sulla distribuzione delle faglie permettono di conoscere il verificarsi dei danni agli edifici. Nell'area studiata non ci sono faglie attive. Il fine della ricerca era analizzare i fattori che possono spiegare la distribuzione e l'orientazione delle faglie subsidenti. Tali faglie sono raggruppabili in sistemi. L'area studiata, la città di Irapuato, è situata nel limite superiore della cintura vulcanica transmessicana (Transmexican Volcanic Belt, TVB), nello stato di Guanajuato - Messico centrale. Sono predominanti le rocce vulcaniche. La subsidenza, evidenziata dalle fratture nel terreno e da faglie subsidenti, sta interessando le infrastrutture urbane di Irapuato. Tale fenomeno tettonico è associato all'inteso regime di emungimento di oltre 1600 pozzi agricoli attivi. La densità dei pozzi per l'agricoltura all'interno dell'area urbana sta contribuendo ulteriormente all'abbassamento del terreno. Ci sono solo 85 pozzi attivi per l'approvvigionamento idrico urbano. I 15 sistemi di faglie sono stati rilevati a Irapuato per una lunghezza totale di 25 km. La velocità di subsidenza è 1.4-1.5 cm all'anno. Lo spostamento verticale accumulato in 10 anni varia tra 2.05-2.15 m. Le faglie sono rilevate topograficamente e tutti i dati geometrici georiferiti sono stati inseriti in un GIS. L'orientamento prevalente delle faglie è N-E. C'è un controllo strutturale sulla deposizione e sulla geometria dei materiali fini e conseguentemente nell'orientazione delle faglie. L'orientamento e la distribuzione delle faglie viene messa in evidenza dalla geometria della deposizione dei sedimenti plastici, prevalentemente argille e limo lacustre e fluviale.*

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Introduction

Subsidence provoked by the intense abstraction of the local and regional aquifer systems is a worldwide problem, especially in urban areas surrounded by agriculture lands (Poland, 1984), because differential soil consolidation of plastic deposits causes vertical displacements. This subsidence is occurring in several regions in Mexican.

Due to the geological, hydrogeological, and climatic conditions of the Mexican Highlands, groundwater is a main water source in continuingly growing demand. The demand is drawn from sectors like agriculture, urban supply, and industry; though agriculture is the greatest consumer, using more than 80 percent of all available water. The central and northern parts of Mexico have arid and semi-arid climate conditions and, in such regions, agriculture well usage exceeds, by twice the magnitude, urban well usage. Irapuato city itself has 85 active wells, while the agriculture sector of the region uses more than 1,600 wells.

Aquifer exploitation—not necessarily overexploitation—provokes collateral damages. When an aquifer system is composed of

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clay and/or claylike units, water abstraction can induce subsidence (which is more related to aquifers plastic materials than to intense abstraction regimes) and differential terrain sinking. Extraction induces flows from aquitards, depressuring them and provoking clay consolidation. Differential terrain sinking originates fractures that became the so-called subsidence faults. Queretaro, Morelia, Irapuato, Salamanca, Celaya, Abasolo, Silao, Aguascalientes and Mexico City are some of the Mexican cities affected by subsidence.

Irapuato city is located in the central part of Guanajuato State, Mexico (Fig 1). It has an area of 225 km^2, mean elevation of 1,724 mosl, and the climate is dry to temperate with a mean annual temperature of 18ºC. The main economic sectors of the city are agriculture and industry.

Geologic framework

Irapuato is located in the Mexican Transvolcanic Belt. Late Miocene is represented by volcanic emissions of intermediate to basic composition. The sub-province Bajio Guanjuantese (where Irapuato is located) is characterized by ranges, plateaus, and plains, over depressions filled with fine sediments and alluvium. Two main lithologic sets exist: first, a plutonic and meta-sedimentary Mesozoic complex outcropping along Guanajuato Range that formed the hydrogeologic basement (Carreón-Freyre et. al., 2005); and second, a domain of volcanic rock and sediments from Medium Tertiary to Quaternary. The Guanajuato Range is affected by an inverse fault system NW-SE. Tertiary structures are represented by the Bajio fault with NW-SE orientation (Martínez et. al., 2005).

Fig. 1: *Irapuato City area in Guanajuato State, Central Mexico.*

Stratigraphy

The Mesozoic rocks are covered by an angular discordant of Tertiary and Quaternary volcanic rocks. Cenozoic volcanic activity formed new topography reliefs where continental sediments were deposited (Fig 2).

The Guanajuato Conglomerate represents the continental Tertiary sediments (Ramos-Leal et al, 2007), and the Losero Formation, constituted by clastic volcanic rocks with intercalations of fine sands, underlies it (Pérez et. al., 1996). Its maximum reported thickness is 1,500 meters. Sands, conglomerates, tuffs and ashes integrate the tertiary volcanic-clastic formation, formed by the Calderones Conglomerate. The andesitic lava flow of El Cedro Formation overlies the Caldorenes Conglomerate.

The volcanic tertiary is represented by the Oligecenic Bufa rhyolite, the Chichindaro Miocenic rhyolite (Ramos-Arroyo et. al., 2004) and the Xoconoxtle Conglomerate produced by the volcanic rocks erosion.

The Quaternary Formations are represented by El Capulin and Las Capillas Formations , outcropped in low areas, and composed of alluvial and lacustrine sediments deposited in depressions, both of them with intercalations of mars, lutites and limestones lenses.

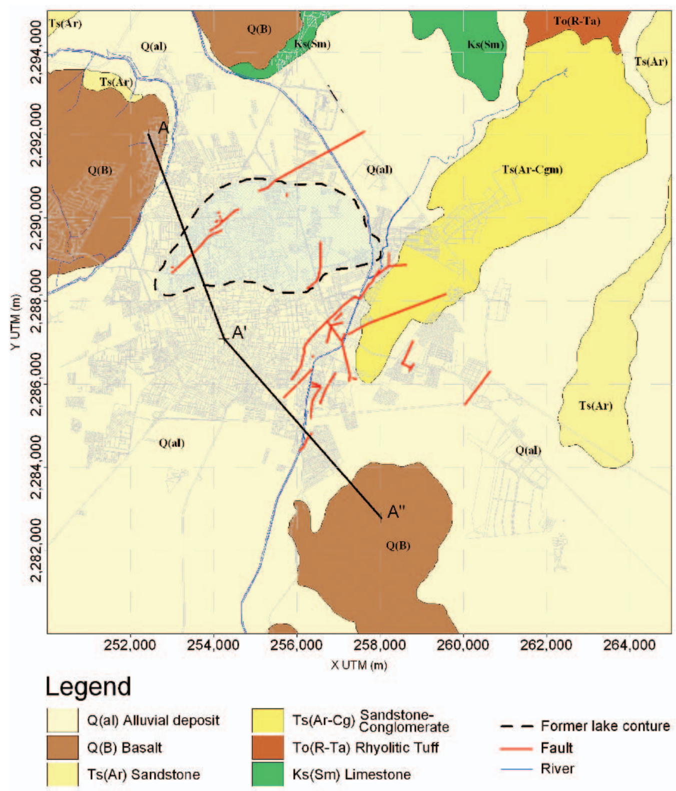

Fig. 2: *Local geology and fault systems, Irapuato, Mexico.*

The local aquifer system

Irapuato valley is filled with alluvial sediments that overlay older igneous rocks. The aquifer system is composed of four permeable units:

1. Clastic sedimentary rocks: a semi-permeable unit defined by semi-compacted conglomerates, sands, and limolites, underlying shallow clay layers;
2. Acidic igneous rocks: a low-permeable unit formed by massive rhyolites and ignimbrites;
3. Basic and intermediate igneous rocks: a permeable unit defined by basaltic and andesitic rocks, with permeability dependant on fracturing;
4. Lacustrine and fluvial deposits: sediment deposits defined by gravel, sand, and limestone layers intercalated by clay and claylike lenses of variable thickness.

Methodology

Geological units and main outcrops were verified. Contacts, wells, faults, and water table information were incorporated into a Geographic Information System (GIS). The previous reported faults (FOSEG, 2001) were verified, and a preliminary fault and fracture identification was done. Position and dimension was obtained using a Total Station and a GPS ASTECH of double frequency. Vertical displacement was measured only in points with distances greater than 0.2 m using a distanciometer Spectra Precision with 1mm precision.

A schematic geological profile was integrated with available information. Although well owners must give well data to the National Commission of Water, (CNA), local water authorities have only nine lithologic columns. Available geoelectric soundings were used to validate the proposed unit distribution in the profile.

The aquifer system was characterized using reported information, well lithological data, and geological maps (1:50,000 scale). The geologic conceptual model was elaborated following the deposition patterns given by the regional historic geology, regional and local geology (Schroeder, 2010).

Results

Since 1983, the Municipality received the first faults reports. In 2001 The Guanajuato State Government published a Risk Atlas, which included the Irapuato faults (FOSEG, 2001). The faults were not geopositioned. In this study, the faults were grouped in systems; this selection considers fault position, orientation and evolution, showing that the fault systems had evolved in six years. In late 2006, fifteen faults systems were recognized (Fig 3), most of them are located in downtown Irapuato. Total fault length was 25.23 Km, with a NE preferential direction. Some fault systems show a perpendicular direction, due to thickness and distribution of sediments that fill the central part of the present urban area.

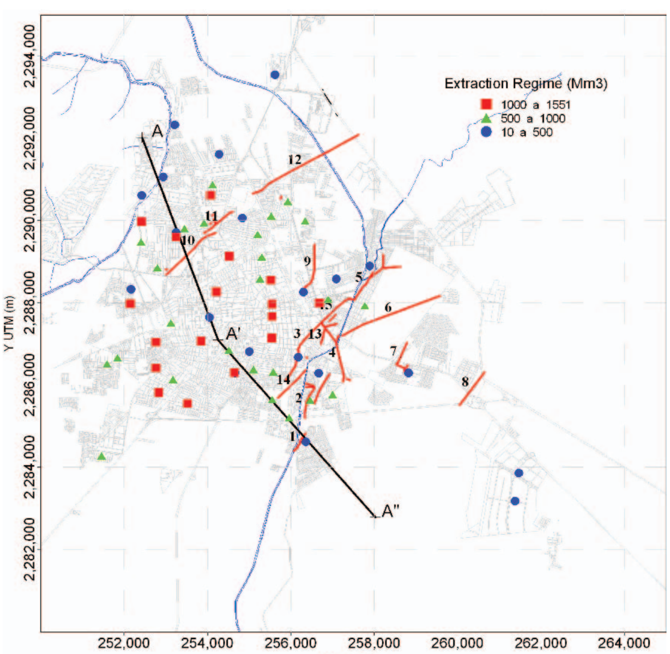

Fig. 3: *Fault system and wells with abstraction regimes.*

The **systems 10, 11 and 12** (Fig 3), located in the northwest part of the urban area can be associated with the limit of the former Lake Eraitzicutzio with basaltic spills from the Arandas Hill (Fig 2). The fault's alignment matches up with the abrupt change of the thickness of the clayed sediment. The vertical displacement range varies between 1.5 to 2.5 cm/year

The Guadalupe Bridge, a historical construction, is crossed by a fault of 2.5 Km length (**system 3**). This system represents the southeastern limit of the former lake and coincides with the contact between the lacustrine sediments and the Tertiary conglomerate, a product of the erosion of the volcanic material.

System 9 (Plan Guanajuato), according to its position and geometry, can be related to surface manifestations of non-consolidate material of Rio Guanajuato former meanders. This system does not follow the pattern of the other systems located in downtown. Local vertical displacement range varies between 1.5 to 2.1 cm/year.

System 6 (Campo Militar), cannot be related to the possible factors that control the position and orientation of the other systems, although it also displays a northeastern direction. However, it has a different evolution. This fault are formed into the Tertiary conglomerate.

The **systems 4, 13 and 15** could be explained by the presence of fine sediments related to the Guanajuato river meanders. All faults converge at the area near Guanajuato river.

The **systems 7 and 8** are delimiting a topographic depression filled with lacustrine sediments that give it its geometry. Its extension is relatively short in comparison with the other systems.

The 15 fault systems have affected more than 400 buildings. Rodriguez and coll. (2006) estimated that damages exceed two million US dollars by late 2006.

Total abstraction amount is unknown. The greater urban extraction volumes are concentrated in downtown. Urban wells with annual extraction ranging from 1,000 to 1,550 M/m^3 and 500 to 1,000 M/m^3 are located in the middle of the main fault systems (fig. 3).

As a consequence of urban and agricultural abstraction, withdrawal from the main water table is also located downtown, with deep wells (200 to 250 m) located in the same area. Most of the agricultural wells were drilled to 100 m, though important producers are now drilling new wells to 200-300 m depth.

The shallow agricultural wells influence the upper part of the aquifer, contributing to the reduction of water pressure and an increase in land compaction. Small and isolated perched aquifers, locally confined by fine sediments, exist in the central part of the urban area. These aquifers provide explanation for the small fractures of discordant geometry in fault systems 7 and 8 (fig 3).

In general, faults and fractures are produced in the borderss between volcanic rocks and fine sediments and/or where there are abrupt changes in sediment thickness. Volcanic rocks deposits coming from the highlands of Guanajuato Range and Arandas Hill delimit lacustrine fine sediments

The contacts between lacustrine sediments and Quaternary lava flows or Tertiary conglomerates can be considered as weakness zones where vertical displacement discontinuities can produce fractures that evolve to faults. Terrain sinking is greater where clay layers, instead of clay-like lenses, provide the aquifer semi-confining.

The analysis of the magnetic survey (SGM, 2005) can give us information related to big structures that can control the geometry of the deposited material. The magnetic anomalies indicate a maxi-

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mum in the central part of urban area, anomalies that continue to the north. Magnetic highs can be correlated with the basaltic bodies (Arandas Hill), but the geometry of local big structures cannot explain fault orientation.

Discussion

In the first fault survey, some faults were mistaken for fractures due to bad building foundation. Buildings located on the banks of local rivers and/or on clay-filled terrains where the former lake was located also presented fractures due to soil instability. The fault mapping presented in this study, included faults detected in late 2007. Some of them could have a greater extension by early 2010, while still others are appearing.

Terrain faulting and fracturing presented a preferential direction pattern southwest to northeast, indicating structural control due to the geometry of the accumulation of the deformable materials (clay, lime, and clayey layers). There is not a clear tectonic control on the fault orientation and geometry, but the tectonics control the geometry of the sediment deposits and, in some ways, the orientation of the faults.

Subsidence is originated by water extraction of an aquifer system composed by aquitards and/or plastic material (like clay). The depressurizing of these materials provokes its consolidation. In Irapuato, the geological processes that have filled the valley have formed large clay and clayey layers. Additionally, the Guanajuato and Silao river meanders created irregular distribution of fine sediments. Eraitzicutzio Lake caused one of the main clay depositions, for its desiccation occurred in early 1800. This geometry is known through oral tradition, although there are old maps where its presence is reported (McIntocht et al., 2002). The fault systems 10, 11 and 12 are related to the north-west margin of the former lake (Fig 2 and 4). In the Profile A-A´-A´´ the fault system 10 reflects the western margin of the lacustrine deposits.

Faults are delimiting areas where clay dominates beside deep urban wells and shallow agriculture wells. The greatest extraction volumes are extracted from the deep urban wells.

Irapuato City presented a particular situation regarding urban and agriculture wells. Rodriguez and Lira (2008) reported Irapuato as a city with the greatest well density inside an urban area. Agriculture abstraction of the more than 400 active wells inside the urban area is unknown, but is estimated at least twice that urban extraction. These extractions are contributing to the depressurization of the clay and clay-like materials.

Fault orientation of the system (Plan Guanajuato, Morelos/Río Guanajuato and Desnivel/Solidaridad) is related to the irregular distribution of sediments attributed to paleo-channels of the Guanajuato and Silao rivers.

The temporal increasing of subsidence velocity in Puente de Guadaluape and Juan Escutia areas are related to increased abstraction, and new wells which are being drilled in its surroundings (Rodríguez et. al., 2006)

Subsidence and its associated faulting in Irapuato are related to the consolidation process of deformable materials, due to the joint urban and agriculture extraction. The observed subsidence velocity, 2 cm/year, agrees with the accumulated displacement, which, in some areas, has been 2.15 meters and 2.05 meters during the last ten years.

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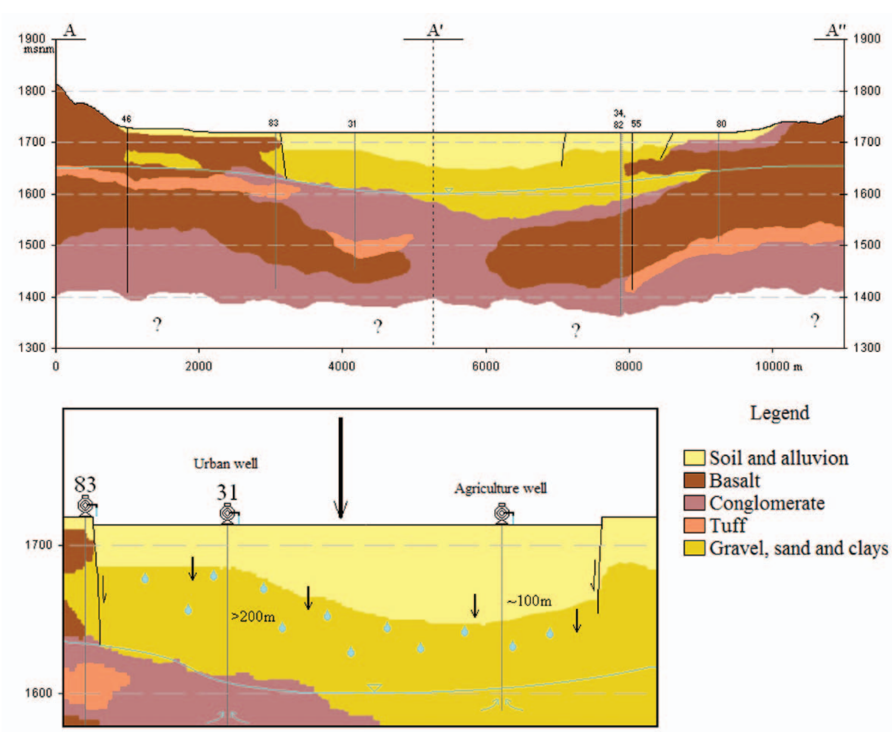

Fig. 4: *Geological profile A-A´ including lacustrine sediments related to former lake.*

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