# Is there a tectonic component to the subsidence process in Morelia, Mexico?

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**Abstract** Subsidence has been a common occurrence in several cities in central Mexico for the past three decades. This process has caused substantial damage to the urban infrastructure and housing in several cities. Given the observed rates of subsidence and reported damage, it has become a major factor to be considered when planning urban development, land-use zoning and hazard mitigation strategies for the 21st century. In the case of Morelia there is evidence that subsidence is a complex phenomenon, where both soil consolidation and tectonic factors come into play. We present a satellite geodesy analysis of surface deformation in Morelia complemented with Ground Penetrating Radar and Seismic Tomography surveys of the La Colina fault, the most active feature within the urban area. These data provide insight into the tectonic component, which overlaps the groundwater extraction, and soil consolidation processes observed in key areas of the city.

**Key words** InSAR; fault; subsidence; tectonics; Morelia, Mexico

## INTRODUCTION

Subsidence documented in urban areas in central Mexico (e.g. Farina *et al.*, 2007; Cabral-Cano *et al.*, 2008, Osmanoglu *et al.*, 2010; and references therein) is usually associated with aggressive extraction rates and a general decrease of underlying aquifer static levels. This human-induced phenomenon promotes soil consolidation, deformation and development of faulting that ultimately causes severe damage to buildings and other urban infrastructure. However, evidence in the city of Morelia (e.g. Garduño-Monroy *et al.*, 2001) suggests a more complex scenario, where ground-water extraction cannot solely explain the surface deformation distribution and may also be affected by the regional stress field from the Chapala–Tula Fault zone (Johnson & Harrison, 1989). The city of Morelia is thus a very good candidate for a detailed InSAR spatial distribution analysis complemented with selected detailed subsurface investigations based on GPR and seismic tomography. Our new data provide new insight into the tectonic component, which overlaps with groundwater extraction and soil consolidation processes in key areas of the city.

## APPROACH

The city of Morelia, in central Mexico has experienced active fault development within its urbanized area, first recognized in the early 1980s and throughout the 1990s (e.g. Avila-Olivera, 2008). Currently there are nine NE–SW trending faults known throughout the Morelia urban areas (Fig. 1).

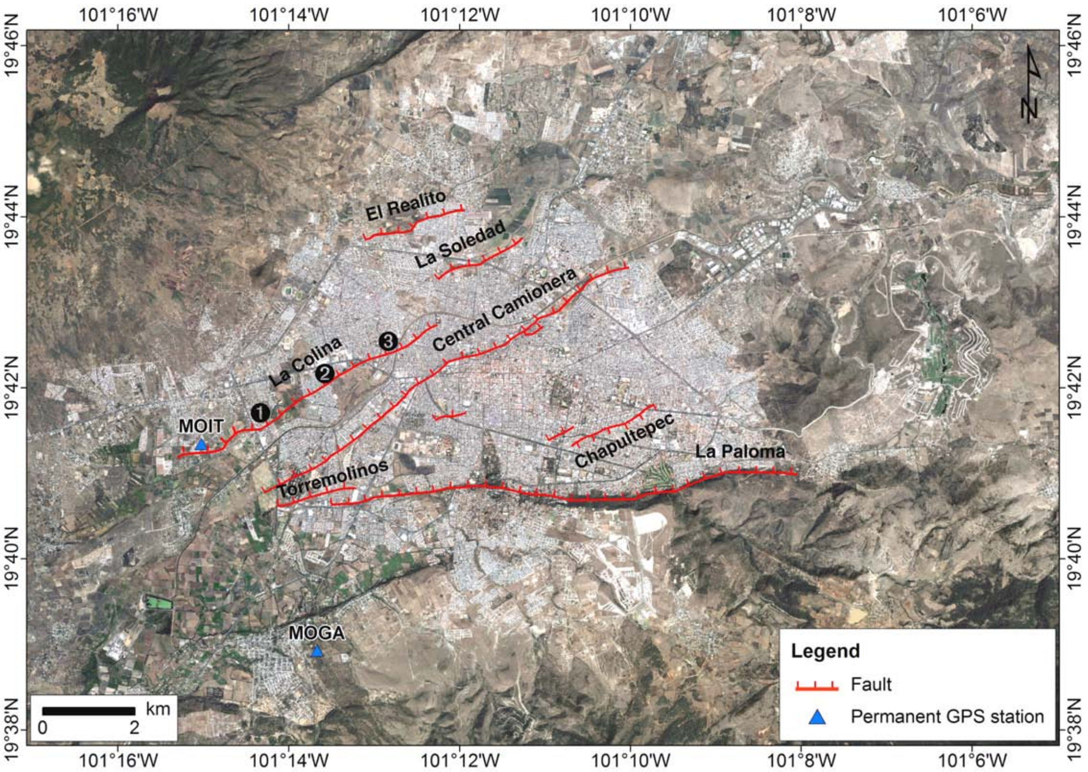


**Fig. 1** Location of study area. Principal faults in Morelia overlapped onto Google Earth high-resolution imagery. Numbers show locations of the GPR-seismic tomography sections.

The increasingly damaging faulting process in Morelia has led us to use available ENVISAT-ASAR (Advanced Synthetic Aperture Radar) archive data at the European Space Agency to create an integrated displacement map derived from a Persistent Scatterer Synthetic Aperture Radar Interferometry (PSI) analysis. The highest subsiding areas were then studied in detail with GPR and seismic tomography techniques.

## Satellite geodesy

Twenty ENVISAT-ASAR scenes acquired between 12 July 2003 and 3 October 2009 were used to generate interferograms with the Delft Object-oriented Radar Interferometry Software (DORIS; Kampes & Usai, 1999). Precise orbits from the Delft Institute were used to minimize orbital errors (Scharroo & Visser, 1998). The 22 January 2005 acquisition was selected as the master scene to minimize the effects of spatial and temporal baselines. The study area was cropped from each SAR scene acquisition and oversampled by a factor of two in range and azimuth to avoid under sampling of the interferogram, especially during resampling of the slave acquisition. Further processing included stacking of interferograms relative to a single master image, a selection of strong scatterers visible in all interferograms and unwrapping of their phase changes through time. These strong scatterers were then filtered to detect and remove the atmospheric phase contribution. Finally they were georeferenced and the line of sight displacement rate for each permanent scatterer was generated (Fig. 2). We also used data from two relatively new permanent GPS sites (Figs 1 and 3) as an aid to improve calibration of InSAR determined subsidence.

Although the spatial resolution of ENVISAT-ASAR based InSAR products is very good, its temporal resolution is variable depending on the frequency of acquisitions. In order to provide better temporal resolution for selected areas we installed two permanent GPS sites. The MOGA station serves as a fiducial site to aid in further detailed GPS surveys of these faults, while the MOIT station is located close to the western segment of the La Colina fault.

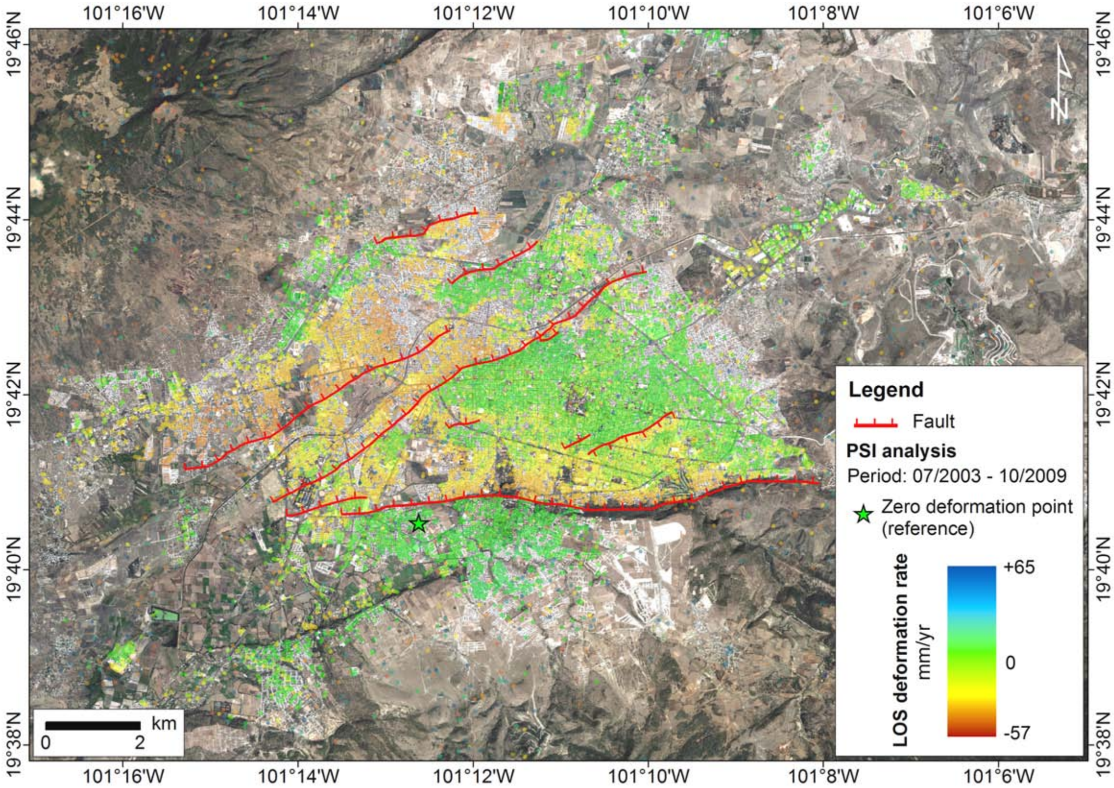


**Fig. 2** Persistent Scatterer InSAR (PSI) displacement map of Morelia overlapped onto Google Earth high-resolution imagery.

The coordinate time series for both GPS stations (Fig. 3) were determined using a standard precise point-positioning analysis of the raw code and phase data using GIPSY software from the Jet Propulsion Laboratory (JPL). Daily station coordinates were estimated in a non-fiducial reference frame and then transformed to ITRF2005 using daily seven-parameter Helmert transformations from JPL.

The PSI derived line of sight displacement map (Fig. 2) shows that La Colina fault on the northern and northwestern sector of the city is the highest subsiding area, with maximum annual rates over –50 mm/year. Lithological mapping (Avila-Olivera, 2008) show a basaltic lava sequence outcropping in the northern and northwestern area of the city where high subsidence rates are also observed. These areas were further investigated using near-surface geophysical exploration methods.

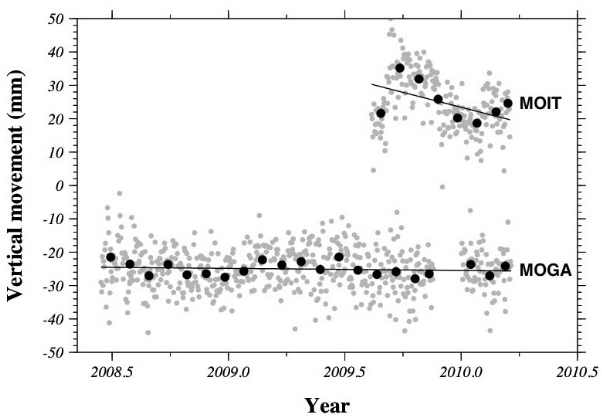


**Fig. 3** Vertical time series for MOGA and MOIT permanent GPS sites. See Fig. 1 for site location. Grey dots are daily solutions and black dots are averaged weekly solutions.

### Ground Penetrating Radar

For this study we used a Geophysical Survey Systems Incorporated (GSSI) SIR-3000 console, a GSSI 200 MHz antenna and Radarteam 40 and 70 MHz antennas. All surveyed sections (Fig. 4) were georeferenced with geodetic dual frequency GPS receivers using post-processing kinematic survey techniques referenced to the MOGA site. GPR profiles on the study area were surveyed using a wheel encoder attached to the GPR console-antenna array. Acquisition was done at 100 scans/m, 1024 samples/scan and 8-bits/sample. Processing of this data set included filtering using an acquisition Infinite Impulse Response vertical and a vertical filter boxcar. We also applied a time (horizontal axis) filtering to enhance the response of the surveyed strata and its structures. De-convolution removed unwanted multiple reflected energy arrivals. The final steps were the migration to position all reflectors to their true spatial location and compensate for any distortion induced during acquisition and the wave propagation.

### Seismic tomography

Seismic Refraction Tomography (SRT) is an effective tool for horizontal, lateral and vertical characterization of structures. The refraction surveys included four profiles (Fig. 4) using a 48-channel 24-bit Geometrics Stratavisor NZ seismograph and 14 Hz natural frequency vertical Oyo-Geospace geophones. Each profile consisted of five consecutive lines of 12 geophones deployed at 2-m intervals, with an overlap of 2 m between lines. The seismic source used was an 8 kg sledge-hammer vertically impacting on a 20 kg ground-coupled steel plate. Five impacts were stacked at each shot point to enhance data signal-to-noise ratio. Processing was done using the SeisImager Refraction Modeling package, which includes an interactive method to perform the nonlinear travel time tomography in two dimensions.

## DISCUSSION

The satellite geodetic analysis of surface deformation in Morelia since 2003 documents more than –50 mm/year of line of sight motion in selected sectors of Morelia. The largest displacement rates were detected on the hangingwall of the La Colina Fault (Figs 1 and 2). Initial data for the MOIT GPS station located ~200 m north of the fault (Fig. 3, top) indicate rapid periodic vertical motion. This observation is consistent with the westward propagation of the fault, which had no surface expression in this part of the city until recent years. Detailed geophysical surveys across this fault (Fig. 4) indicate that while the surface expression may only hint at what appears to be a single fault trace, subsurface imaging instead reveals a zone of closely-spaced shallow faults 20–40 m wide. The largest fault dislocation was observed at the Manantiales sector (8–12 m displacement; Fig 4). Other sectors, such as the Rio Grande sector, show less that 6 m of dislocation.

Assuming a constant, linear subsidence rate in the past, similar to the InSAR observed rates, and based on the interpretation of the fault dislocation imaged by the shallow GPR and seismic tomography, we propose that the La Colina fault may have been active for at least 240 years and clearly pre-dates the intense water well extraction of the last decades. Of course it is possible that groundwater extraction has increased the deformation rate.

The documented deformation suggests the existence of a tectonic component overlapping with the soil consolidation and its related subsidence. Therefore, it is possible that at least some of the E–W faults observed within the city of Morelia may be an active segment of the Morelia–Acambay fault system and part of the larger Chapala–Tula Fault zone (Johnson & Harrison, 1989). This suggestion may also solve the apparent contradiction of the basaltic lava sequence out-cropping in the northern and northwestern area of the city where high subsidence rates are observed. We are thus documenting that at least the La Colina fault in Morelia responds to an active regional stress field, which may be enhanced by local soil consolidation effects.

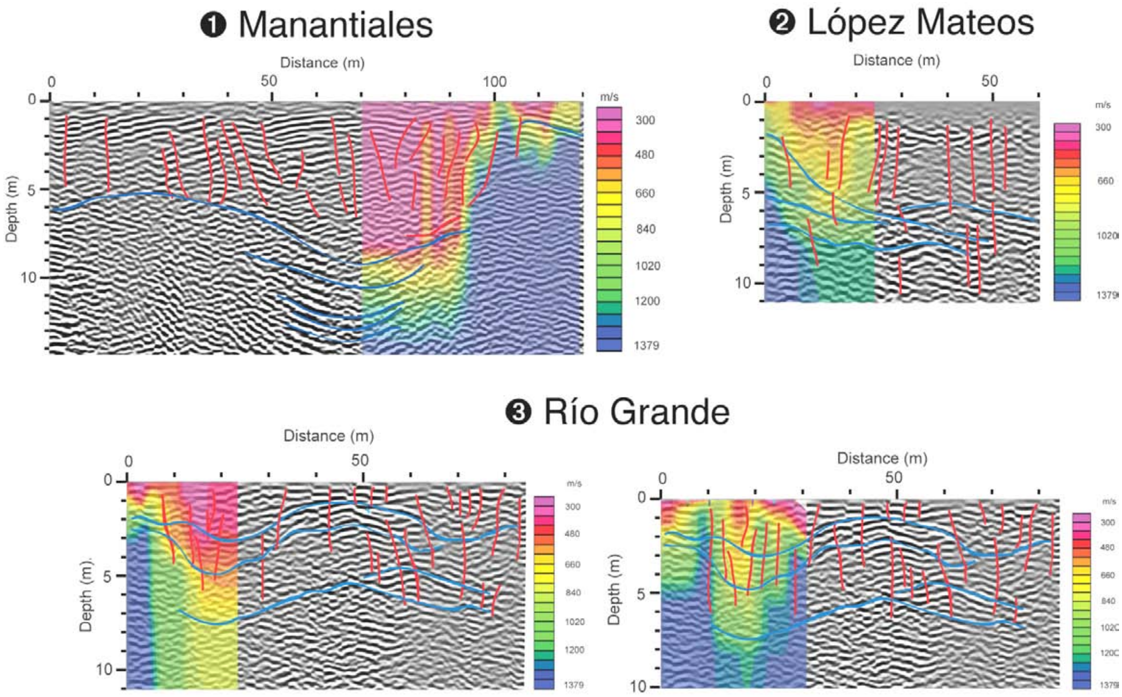


**Fig. 4** Interpreted (lines) examples of surveyed seismic tomography (colour) sections overlapped onto GPR radargrams (greyscale images) in three areas of the La Colina fault. See Fig. 1 for the location (circled numbers) of each section.

## CONCLUSIONS

1 We propose that the La Colina fault may have been active for the past 240 years, clearly predating the intense water well extraction period from the last 20–30 years.

2 While some of the high subsidence features of the InSAR displacement maps show continuous rates along the fault strike and a well defined gradient across strike such as the La Paloma fault (Fig. 2); in other instances such as the eastern portion of the La Colina fault, the rapidly deformed area does not conform to the linear fault pattern and may be better explained as the concentrated subsidence around and intense groundwater extraction area.

3 The observed conditions suggest the existence of a tectonic component overlapping the soil consolidation and its related subsidence. These observations support the hypothesis that at least some of those faults within the city of Morelia may be an active segment of the Morelia–Acambay system and part of the larger scale Chapala–Tula Fault zone.

4 The wide swath of intense faulting and fracturing along the major fault traces indicates that current land use and building code criteria for determination of hazard areas along the fault zones is inadequate and should be revised.

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