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# Subsidence in the geothermal fields of the Taupo Volcanic Zone, New Zealand from 1996 to 2005 measured by InSAR

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**Abstract**

A number of the geothermal systems in the Taupo Volcanic Zone (TVZ), New Zealand, have been utilised on a large scale to provide heat and to generate electricity, in some cases causing areas of localised subsidence. Subsidence monitoring using field-based surveys is practically constrained by limits to available resources so we have investigated the use of satellite differential radar interferometry (InSAR) for this purpose. Using ERS and Envisat radar data spanning 1996 to 2005, we have mapped the deformation at five of the heavily utilised geothermal fields of the TVZ. Subsidence signals were identified at the Ohaaki geothermal field from 1999–2004, and at Wairakei–Tauhara from 1996–2005, where our measurements compare well with coeval levelling data across the wider deformation field. Subsidence was also measured at Rotorua from 1996–2000. In favourable conditions, the InSAR measurements provide a relatively dense spatial coverage of the deformation field that extends well beyond the boundaries of the geothermal systems and beyond the scope of the networks of levelling benchmarks. In the case of the Wairakei–Tauhara geothermal field, using InSAR it is now possible to improve the spatial resolution near the field margins and to interpret the subsidence signals in the context of the wider, more regional, deformation. Our data also provide new insights into possible fault motion at the Mokai geothermal field occurring around the time of the commissioning of its first power station. We note, however, that the InSAR technique is not without limitations. High gradient subsidence features are poorly represented, although this can be resolved to some extent via a trade-off in data processing. Temporal decorrelation, a well known problem for this technique, is also an issue for TVZ geothermal fields. Therefore, we find that it is possible to provide fortuitous snapshots of the deformation at the TVZ geothermal fields, but operational monitoring using InSAR would be difficult as the proportion of suitable interferograms is low.


*Keywords:* New Zealand; Taupo Volcanic Zone; Subsidence; Geothermal fluid extraction

## 1. Introduction

The Taupo Volcanic Zone (TVZ) in New Zealand is an actively extending back-arc rift, developed in association with the subduction of the Pacific plate beneath the Australian plate. It is characterised by extensive volcanic and seismic activity (Wilson et al., 1995), which is accompanied by an exceptionally high heat output (~700 mWm$^{-2}$) channelled through twenty-three geothermal systems (Bibby et al., 1995).

Many commercial and domestic operations are permitted to extract small to medium quantities of

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water from a number of these geothermal systems and since the 1950s, some of the higher temperature fields (>220 °C) have been utilised on a larger scale to provide electricity (e.g. Carey, 2000). The reduction of subsurface pore pressure at some of these fields due to fluid extraction (without replacement) has affected the natural surface features and caused localised subsidence of up to 15 m (since 1950, at the centre of one bowl at Wairakei), which is more than in any other development involving fluid withdrawal (Allis, 2000). Measuring the spatial and temporal changes in the subsidence pattern can provide constraints on the permeability and compressibility properties of the compacting formations. These are important parameters for predicting future subsidence (Allis and Zhan, 2000). Monitoring of this subsidence in the TVZ is important to identify areas of infrastructure potentially at risk of structural damage and to reduce the impact of future development of the geothermal fields.

The extent and rate of subsidence at geothermal fields in the TVZ is currently measured by precise levelling across networks of benchmarks, repeated at intervals of one to five years (e.g. Allis, 2000). Changes in future development strategy, involving extraction and injection of fluids, may affect the size of the areas that will need to be monitored. Other field-based techniques, such as differential and continuous GPS, are also available and have been used in the TVZ to monitor deformation (e.g. Darby et al., 2000; Beavan and Haines, 2001), but the spatial density and repeat rate of field-based surveys are practically constrained by limits to available resources.

Differential Synthetic Aperture Radar Interferometry (InSAR) is a technique capable of measuring surface subsidence to centimetric precision over hundreds of square kilometres with a high spatial resolution (nominally ~25 m) (Massonnet and Feigl, 1998). Differential InSAR has been used successfully to measure deformation caused by geothermal fluid extraction, for example at East Mesa, California (Massonnet et al., 1997); Coso, Calfornia (Fialko and Simons, 2000; Vasco et al., 2002); and Cerro Prieto, Mexico (Carnec and Fabriol, 1999). It was also applied to two geothermal fields of the TVZ with mixed success (Hole et al., 2005b,c). This paper represents the first attempt to measure subsidence due to geothermal fluid extraction at all geothermal fields across the TVZ using InSAR. The study has two main objectives: firstly to assess the feasibility of using InSAR to measure the subsidence caused by geothermal development in the TVZ, and secondly to improve the ability to monitor future subsidence in this area.

## 2. Geological and hydrological setting

The TVZ covers an area of 40 km by 150 km (Fig. 1) and is defined by the envelope of active volcanism in the TVZ over the last two million years (Wilson et al., 1995). The TVZ is extending in an NW–SE direction at an average rate of 8 mm/year, north of Lake Taupo (Darby et al., 2000). The extension is not uniform in time or space. Geographically, it is divided into segments of active, largely normal, faulting in the central and western parts of the TVZ separated by non-extending "accommodation zones" (Rowland and Sibson, 2001). The volcanic activity is also segmented in nature: the central part is an area of extensive rhyolitic volcanism, producing over 10,000 $km^3$ of material from several large caldera systems; whereas andesitic volcanism predominates to the north–west and to the south. The depression left by regional tectonic subsidence and caldera collapse has been filled with rhyolite lavas and poorly- to non-welded ignimbrites interbedded with fluvial and lacustrine sediments, which in places is at least 2–3 km thick (Risk et al., 1999; Wood et al., 2001). Basement Mesozoic sandstones (graywacke), are found at the eastern and western margins of the TVZ but the composition of the crust beneath the Quaternary deposits in the TVZ itself is not fully understood (Stern et al., 2005).

A simplified representation of the structure and hydrology of the TVZ is given in Fig. 2. The hydrothermal convection is driven by a heat source at depth, the origin of which remains the subject of much debate (Hochstein, 1995). Conductive heat transport between the ductile base of the crust at 16 km (Stratford and Stern, 2004), and the bottom of the brittle convective region at 8 km (Bibby et al., 1995) can only supply 60% of the observed heat flow at the surface, so heat must reach the convective zone by other mechanisms such as repeated intrusion from the mantle (Bibby et al., 1995). Stress redistribution associated with such intrusions of ductile material at depth could lead to large temporal and spatial variations in surface deformation rates.

Within the shallow (0–3 km) volcanic-sedimentary sequences, the highly permeable layers (aquifers) act as geothermal fluid reservoirs (containing liquid or vapour), and have interlayers of poorly permeable rocks (aquitards). The water heated at depth forms narrow convective plumes which rise and spread laterally into the shallower aquifers. The hot fluids may boil and escape to the surface as water or steam via permeable paths though the aquitards provided by faults and fractures (e.g. Soengkono, 1999, 2000). Through boreholes, fluids may also be discharged as steam-brine