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Structures involved in the vertical deformation at Lake Taupo (New Zealand) between 1979 and 2007: New insights from numerical modelling

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ABSTRACT

Since 1979, repeat levelling measurements have been conducted on the lake filling the caldera of the dormant Taupo rhyolitic volcano in the North Island of New Zealand. Interpretation of these data through numerical modelling provides information on the structures involved in the relative vertical crustal movement throughout the southern end of the Taupo Volcanic Zone (TVZ), an area of active back-arc extension. The best-defined feature is a long term global subsidence of the northern part of the lake (7 mm yr^{-1}) due to the cumulative effect of the crust stretching and a deep deflation source. This long term subsidence is occasionally disturbed by strong short-term uplifts linked with overpressure sources located below the northern part of the lake, near active geothermal fields. Episodes of uplift can be attributed to various combinations of the following two processes taking place beneath the geothermal field (1) Movement or formation of rhyolitic magma (deepest sources) (2) Pressurization of the shallow hydrothermal fluid reservoir that traps volatiles exsolved from a crystallizing rhyolitic magma (shallowest sources). The pressurization of the shallow hydrothermal system gives rise to tensional stresses in the upper crust, resulting in seismic and aseismic fault ruptures. Slow slip motion of the Kaiapo fault decouples on a short-term time scale the ground deformation pattern on both sides of the fault. Our results, discriminating what parts of the deformation are due to the regional setting, the hydrothermal circulations and the seismic activity, reveal that each seismic swarm is preceded by 1 to 3 years of inflation of the eastern part of the lake. This systematic behaviour may allow us in the future to better predict the occurrence of the seismic swarms below the lake.

1. Introduction

Since the 20th century, lake levelling measurements have been used as natural tiltmeters to constrain ground deformation by evaluating the relative water height changes measured at different sites on a lake (Wilson and Wood, 1980; Hamilton, 1987; Hudnut and Beavan, 1989; Otway and Sherburn, 1994). In the Taupo Volcanic Zone (TVZ) of New Zealand, repeated lake levelling measurements have been conducted since 1979 in the lake filling the caldera of the Taupo dormant volcano. Data covering the period 1979–1999 has been already well described by Otway (1986, 1987, 1989), Otway et al. (2002), Otway and Sherburn (1994) and Smith et al. (2007) and reveal a long-term subsidence in the northern part of the lake occasionally disturbed by short-term uplifts in localized areas. Except for Smith et al. (2007) who have modelled the subsidence observed between 1986 and 1999 by a Mogi point dilatation at 8 km depth, the cause of the vertical deformation evolution through time has not been well constrained. Thus the location and the shape of pressure sources and the mechanisms at the origin of vertical deformation fluctuations at Lake Taupo between 1979 and 2007 remain poorly known. Regional rifting, geothermal fields and fault motions, which all characterize the Taupo area, can strongly affect the ground deformation and must be distinguished from any magmatic deformation. Ellis et al. (2007) investigate the effect of a hypothetical magmatic inflation event in the subsurface magmatic system of Taupo. The models demonstrate that surface displacements associated with magma body inflation up to 10 km^3 in volume at 15 km depth beneath Lake Taupo may be almost entirely hidden. It is thus important to understand the origin of the current deformation recorded at Lake Taupo and to discriminate the part of the deformation linked with regional rifting, geothermal fields and fault motions. The aim of this paper is to constrain the location and the origin of the sources and the structures involved in the vertical deformation at Lake Taupo between 1979 and 2007. We present an overview of the levelling data recorded between 1979 and 2007 and their interpretation through 3D numerical modelling using both finite element method (FEM), taking into account the regional

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setting (rifting) and the local structures of the TVZ, and boundary element method inversion (BEM).

2. Geological setting

The Taupo volcano is located in the southern part of the rifting continental crust of the TVZ (Fig. 1A, B). The TVZ is about 50 km wide and 200 km long and lies above the oblique subduction of the Pacific plate beneath the North Island of New Zealand and the Australian plate. This zone of crustal thinning and extension is characterized by exceptionally high fracturing expressed by the Taupo Fault Belt, with dominantly normal faults oriented in a northeast direction, high heat flows with numerous geothermal fields, and intense volcanic activity.

The Taupo caldera formed during the voluminous Oruanui eruption about 22,600 years before present (BP) and is now filled by Lake Taupo. Most of the past activity was characterized by rhyolitic eruptions occurring down the eastern side of the Lake Taupo along a NNE–SSW trend (Fig. 1C; Wilson et al., 1995; Sutton et al., 2000; Wilson, 2001). The most recent major eruption took place about 1800 years BP from at least three vents along a NE–SW-trending fissure centred on the Horomatangi Reefs, corresponding to a prominent low-resistivity zone (Fig. 1C; Caldwell and Bibby, 1992; Whiteford et al., 1994).

3. Seismic activity

Seismic activity in the TVZ zone is particularly well marked (Fig. 2A) and is characterized by numerous shallow earthquakes of M_L 2–4 located at depths less than 8 km (Bryan et al., 1999). During the 1979–2007 period, the shallow seismicity (mostly around 5±2 km depth) recorded below Lake Taupo was focused in localized areas beneath the central, eastern and southern parts of the lake (Fig. 2B). The Taupo Fault Belt, north of the lake, was also seismically very active, whereas the northern half of the lake corresponding to the caldera was aseismic. Thus, four main seismic restricted zones can be distinguished (Sherburn, 1992; Bryan et al., 1999): (1) the area east of Scenic Bay (SB in Fig. 1C) extending along the Waihi Fault, (2) the Horomatangi Reefs area, (3) the area near Motuoapa (MA in Fig. 1C) and extending outside of the southern part of the lake and (4) the Taupo Fault Belt, north of the lake.

Fig. 2A represents the cumulative number of shallow earthquakes recorded in the Taupo Lake area between 1979 and 2007. The seismicity distribution is not uniform over time. At irregular intervals, seismic swarms occurred. Such shallow seismic swarms (≤5 km depth) were recorded in February 1983, June–July 1983, March 1984, March 1987, July 1997–December 1998, and December 2000–June 2001 (Fig. 2A, C).

- The first seismic swarm of the study period occurred in February 1983 in the western part of the Taupo Fault Belt, around 10 km northwest of Kinloch (KH in Fig. 1C) (Fig. 2C).
- On 16 June 1983, another seismic swarm began and was followed by 5 weeks of local seismicity (64 events with magnitudes of 3 or more, Webb et al., 1986). Two clusters can be distinguished, one in the Taupo Fault Belt in the northern part of the lake between Kinloch (KH in Fig. 1C) and Acacia Bay (AB in Fig. 1C) and one near the Horomatangi Reefs (1–2 July 1983, Webb et al., 1986). One week after the beginning of the seismic swarm, a 50 mm normal fault offset was recorded on the Kaiapo fault with ground rupture over a distance of 1.2 km (Grindley and Hull, 1984; Otway, 1986). The Kaiapo fault motion, located east of the first seismic swarm and north of the second one, was not obviously linked directly with the swarms and may reveal a slow slip fault motion.
- The two small seismic swarms recorded in March 1984 and March 1987 occurred below the south-western and middle-western part of the lake, respectively.
- After about ten years of low seismic activity, a new seismic swarm occurred below the lake from July 1997 to December 1998. The epicentres were located near the Horomatangi Reefs and along the southern rim of the caldera (Fig. 2C).
- From December 2000 to June 2001, a strong increase of the seismicity was recorded (Fig. 2A). During this period, two main clusters can be distinguished: one in the area of Scenic Bay occurring in December 2000 followed by one north of the lake along the northern end of the Kaiapo fault occurring between January and June 2001 (Fig. 2C).

Between 2001 and 2007, seismicity has been more or less constant over time without any significant peak of strong activity and is distributed uniformly between each of the seismic zones described above (Fig. 2A and C).

4. Lake levelling data

4.1. Survey method

Since April 1979, periodic (3–4 times per year) lake levelling surveys have been conducted to monitor relative vertical deformation at Lake Taupo. The network consisted of only 7 sites in 1979–83 but following the June 1983 seismic swarm, the network was improved and now consists of 22 sites around the shoreline and on islands (Fig. 1C; Otway et al., 2002). Data are collected with a portable water level gauge that samples the

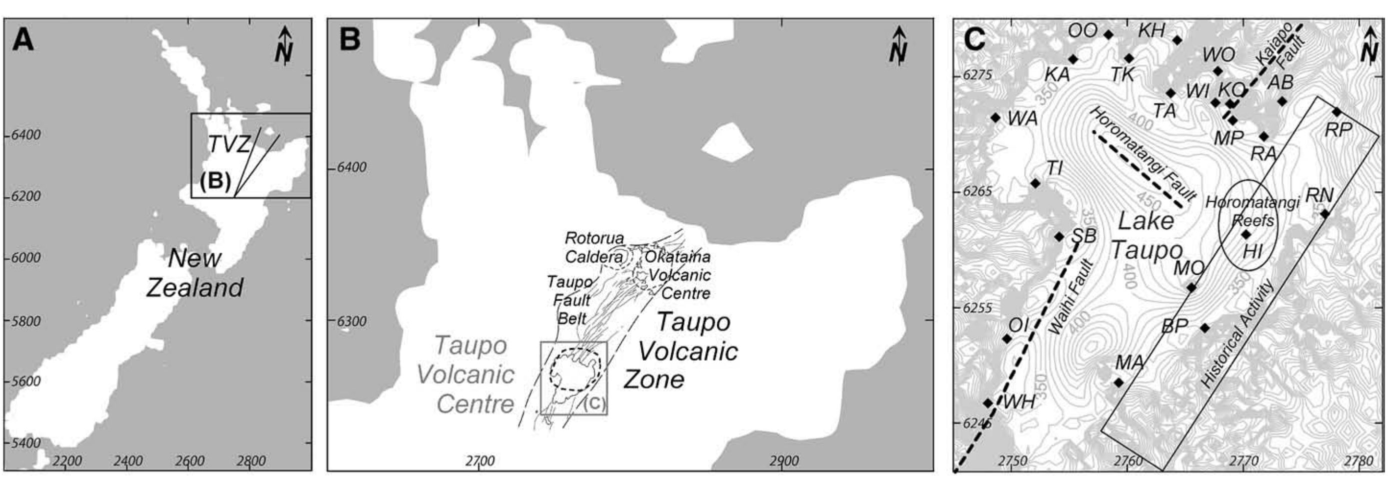

Fig. 1. (A) Location of the Taupo Volcanic Zone (TVZ). (B) Location of the main structures of the TVZ (the main calderas are underlined by dotted circles). (C) Location of lake levelling sites (diamonds), Waihi, Horomatangi and Kaiapo fault traces (dotted lines) and historical activity (NNE–SSW rectangle, after Wilson et al., 1984). Coordinates are in New Zealand Map Grid Projection (km).