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Magnetics and Gravity Image Tectonic Framework of the Mount Melbourne Volcano Area (Antarctica)

F. Ferraccioli[1], E. Armadillo[1], E. Bozzo[1] and E. Privitera[2]
[1]Dipartimento per lo Studio del Territorio e delle sue Risorse (DIP.TE.RIS), Universitá di Genova, V. le Benedetto XV, 5, 16132 Genova, Italy, e-mail:magne@mbox.dipteris.unige.it
[2]Istituto Internazionale di Vulcanologia (I.I.V.), C.N.R., P.za Roma, 2, 95123, Catania, Italy

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Abstract. Mt. Melbourne volcano (Northern Victoria Land-Antarctica) is part of the McMurdo Igneous complex, which spans a considerable time interval between 48 Ma to the Present. It is generally accepted that both the location and the magmatic products of the volcano are genetically linked to Ross Sea rifting and uplift of the Transantarctic Mountains (TAM) rift shoulder. Studies on pyroclastic falls suggest that an eruption likely occurred in the last few centuries. Presently the volcano has a low level of activity which has been highlighted and monitored by means of integrated geophysical networks. After a review of previous geophysical and geological findings at both regional and at a more local scale, in our study we display and interpret newly compiled magnetic and gravity images over the Mount Melbourne area to better constrain the tectonic framework of the region. We propose that the structural setting is dominated by major NW-SE right-lateral strike-slip faults generating uplifted crustal blocks, namely the Deep Freeze Range block and more subsided N-S graben-like structures such as the one in which Mount Melbourne volcano itself appears to be located. Local seismic events could well be associated with the N-S faults within this graben. Gravity data is consistent with crustal thickening beneath the TAM and offshore it highlights together with heat flow data and seismic constraints a NNE trending pull- apart basin with extended crust also linked to the strike-slip tectonics of the region. Local gravity anomalies are also discussed.

1 Introduction

Mt. Melbourne volcano is located in Northern Victoria Land, Antarctica. The Mt. Melbourne (MM) volcanic province (Fig. 1) is a component of extensive rift-related alkaline magmatism referred to as the McMurdo Igneous Complex (48 Ma Present, Tonarini et al., 1997). Mount Melbourne is one of the two active volcanoes, together with Mount Erebus on Ross Island, of the igneous complex. Contrary to Mount Erebus no historical eruptions have actually been witnessed but the presence of fumarolic ice towers and ground heating could attest the presence of near-surface cooling magma (Kyle, 1990 and ref. therein). Indeed a volcanic ash layer, well exposed on the eastern side of the Mount Melbourne volcano has tentatively been dated to be about 200 years old. Furthermore a multi-disciplinary volcanological observatory set up on the volcano within the framework of the Progetto Nazionale di Ricerche in Antartide (PNRA) from 1988 onwards reveals that the volcanic edifice still has active though slow internal dynamics (Bonaccorso et al., 1997).

We compile and interpret new magnetic anomaly and gravity maps of the area to investigate in greater detail, compared to previous studies, how the Mount Melbourne volcano itself straddles the junction between two fundamental tectonic components of Antarctica: the Ross Sea rift, which is part of the active continental scale West Antarctic rift System (Behrendt et al., 1996 and ref. therein) and the highly uplifted Transantarctic Mountains (TAM) rift shoulder. The main interpretation we put forward is that this volcanic area is strongly controlled by strike-slip tectonics and associated transtension in good agreement with offshore seismic results (Salvini et al., 1997). The faults we delineate from magnetics follow old inherited basement faults and are oblique to the rift basin itself clearly imaged from gravity. The structural framework we put forward explains some peculiarities of the Mount Melbourne area itself compared to other sectors of the TAM and has important implications also on present day activity of the volcano.

2 Tectonic framework

The TAM is an impressive, highly uplifted, extensional mountain chain, mainly Cenozoic in age which extends for over 3500 km across Antarctica. Apatite-fission track data indicate that at least two major uplift episodes occurred in northern Victoria Land at 50 and 30 Ma (Balestrieri et al., 1997).

Correspondence to: Emanuele Bozzo

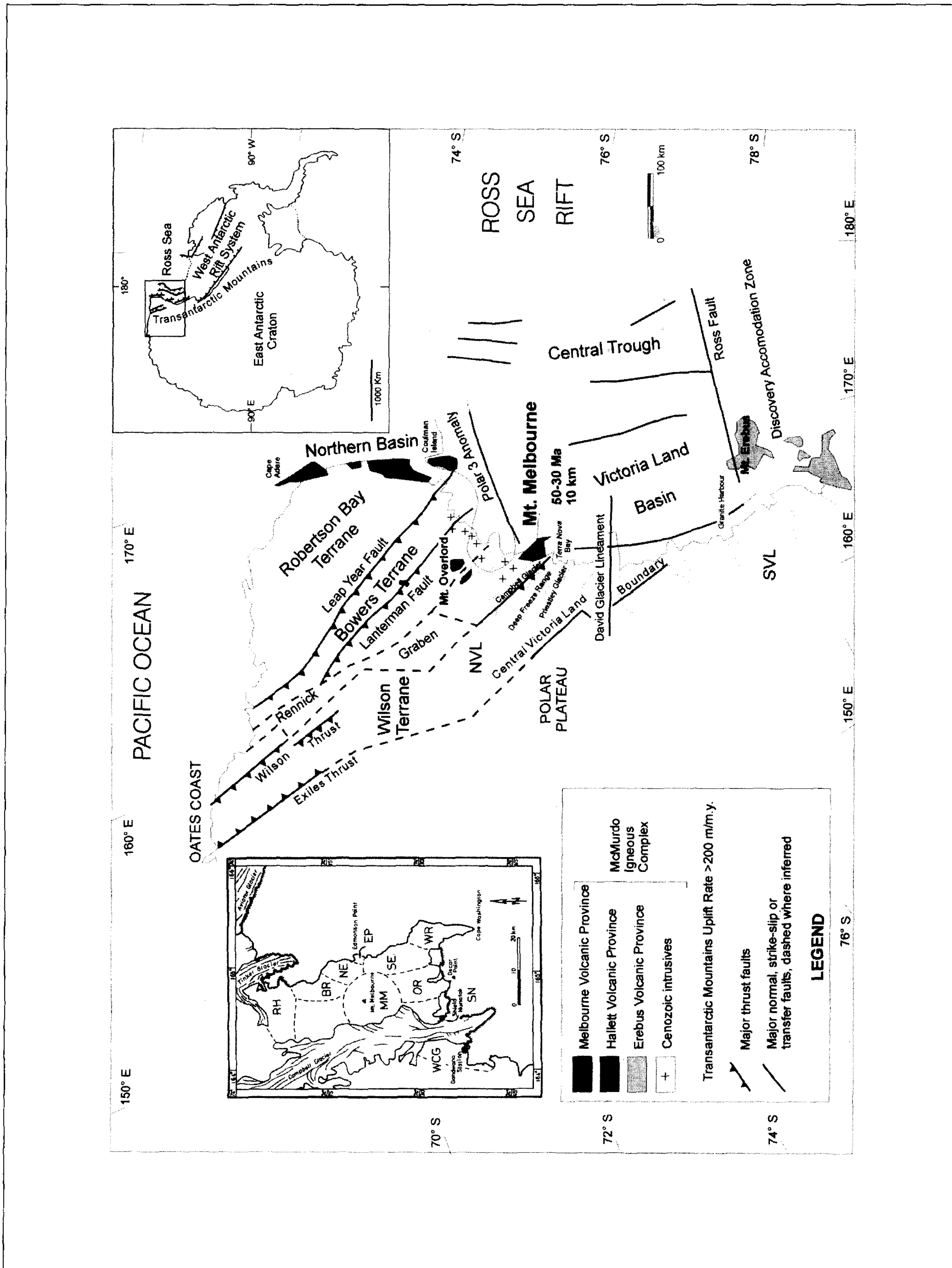

Fig. 1. Tectonic framework and location of Mount Melbourne in the frame of the Mc Murdo Igneous Complex. In the inset the sub-suites (MM, BR, OR, ...) of the Mt. Melbourne Volcanic field are shown (from Wörner and Viereck, 1989).

In Victoria Land uplifted Cretaceous and Cenozoic rift margin crustal blocks of the TAM have also recently been recognized to be super-imposed upon older lower Paleozoic and Jurassic structures (Salvini et al., 1997; Ferraccioli and Bozzo, 1999).

The Ross Sea rift is part of the West Antarctic Rift System, one of the largest but least well known modern rift systems of the world. Seismic investigations throughout the Ross Sea have shown that the rift system has a multi-stage extensional history from at least lower Cretaceous times onward (Davey and Brancolini, 1995 and references therein). Marine gravity anomalies (Coren et al., 1997) support seismic evidence for rift basins in the Ross Sea and confirm the existence of extended crust as thin as 18 km. Magnetic anomalies have been interpreted to reveal that patterns of late Cenozoic volcanic and tectonic activity are very widespread over the rift system (Behrendt et al., 1996). According to several authors none of the rift system can at present be considered tectonically inactive despite the low level of seismicity.

The Cenozoic to present-day tectonic history of the region is reflected in its alkaline rift-related igneous history (LeMasurier and Thomson, 1990) of the McMurdo Igneous Complex to which Mount Melbourne volcano belongs.

3 Related research

At a regional scale MM volcano is located at the intersection of three fundamental tectonic structures (Fig. 1): the NNW trending Rennick Graben (RG), the N-S to NNW Victoria Land Basin (VLB) and the ENE Polar 3 Anomaly. The RG has been interpreted to be a major pull- apart basin, possibly formed in the Cretaceous (Tessensohn, 1994). Short wavelength, high- amplitude magnetic anomalies within the graben are related to Jurassic Kirkpatrick Basalt and to Cenozoic to Quaternary volcanics possible emplaced along its reactivated eastern shoulder (Bosum et al., 1989; Bozzo et al., 1999). Mount Melbourne itself may be located along the western shoulder of the graben, though its master faults are poorly defined in the Terra Nova Bay region (Skinner, 1987).

The VLB (Fig. 1) is the westernmost rift basin of the Ross Sea and has a seismically constrained sedimentary infill up to 14 km thick (Brancolini et al., 1995). There is clear N-S to NNW rift fabric in magnetic anomaly data. High-frequency anomalies flanking the western side of the VLB are interpreted as Cenozoic volcanics penetrating the sedimentary section as revealed by seismic data (Behrendt et al., 1996).

The Polar 3 is a high amplitude magnetic anomaly extending from Coulman Island to MM. It has been interpreted as a leaky transfer fault which links offset segments of the rift system namely the VLB and the Northern Basin (Brancolini et al., 1995). Sub-volcanic alkaline intrusives were emplaced within the fault zone (Bosum et al., 1989). More recently the Polar 3 has been interpreted from seismic data to be a push-up structure linked to compression induced by right- lateral strike-slip deformation along NW-SE faults (Salvini et al., 1997).

Wörner and Viereck (1989) recognize from geological investigations that the Mount Melbourne Volcanic Field is defined by about 60 exposed subglacial and subaerial volcanic centres surrounding the Mt. Melbourne stratovolcano itself. These centres generally consist of tuff rings and hyaloclastites with small lava flows. Sub-suites within the volcanic field have been defined on the basis of morphology, eruptive styles and petrography all of which seem compatible with a rift margin setting (Armienti et al., 1991).

Lanzafame and Villari (1991) performed structural studies on dykes, normal and reverse faults and eruptive fissures. Two roughly orthogonal sets of very recent faults were recognized: NW- SE and NNE-SSW. The two sets are interpreted to be parallel to major unexposed faults of the Rennick Graben and the Ross Sea rift and may reflect crustal extension and uplift.

Little is known about the crustal structure of the MM area. The onshore Bouguer Gravity Map of Redfield et al. (1993) shows a prominent coast parallel decrease in gravity values from close 0 at the coast to 150 mGal moving inland across the TAM with a gradient of about 2.2 mGal/km. This gradient is less than the 3 mGal/km at the south of MM area suggesting that crustal thickening beneath this TAM block is less sharp than to the south.

O'Connell and Stepp (1993) propose a seismic P-wave velocity model for the Deep Freeze Range area, which shows the crust adjacent to MM to thicken from about 20 km at the coast to about 30 km at 60 km inland beneath the TAM. The same authors also interpret the seismic data to reveal a major high-angle fault between the TAM and the VLB dipping to the SE.

4 Magnetic and gravity images

Aeromagnetic and ground magnetic data over this sector of Victoria Land have recently been compiled into a single, as far as possible coherent data set (Chiappini et al., 1999). We further refined this compilation effort to obtain more structural information over the Mount Melbourne quadrangle at the transition to the Ross Sea rift.

The original data were acquired during two different campaigns (Damaske, 1989; Bozzo et al., 1997). For the first survey, flight altitude over the TAM was 3660 m (a.s.l.), while over the Ross Sea section it equaled 610 m (a.s.l.); for the second, all magnetic measurements were taken at 2700 m (a.s.l.). Line spacing was equal to 4.4 km, while the tie line interval was 22 km for both surveys. Different survey layouts and processing techniques resulted in conspicuous mismatches between the surveys, which may in part have hindered interpretation. To integrate datasets new microlevelling techniques were first applied to individual surveys following a frequency domain approach (Ferraccioli et al., 1998). Original IGRF (International Geomagnetic Reference Field) field was added back to the data and the DGRF90 (Definitive Geomagnetic Reference Field 1990) model for the ap-

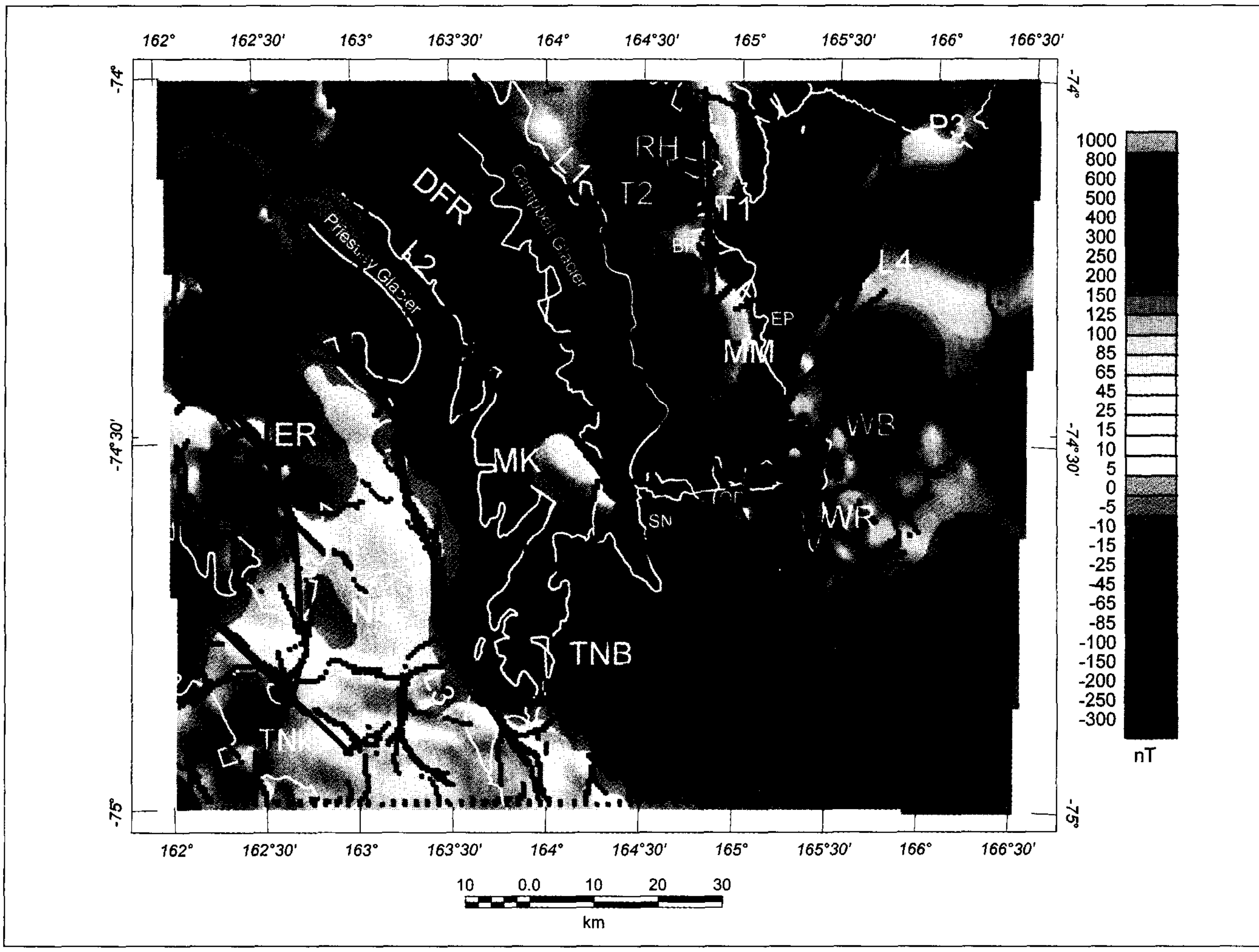

Fig. 2. Total magnetic field anomaly map. Black dots indicate the local maxima of horizontal gradient of pseudogravity while red lines show the main recognized lineaments. L1 is along the eastern flank of the Campbell Glacier; L2 is along the eastern flank of the Priestley Glacier and along the eastern side of the Mt. Keinath Anomaly (MK); L3 is from Terra Nova Bay (TNB) to the east of the Eisenhower Range (ER); L4 is from Washington Ridge (WR) till longitude 166 (Aviator Glacier). The other acronyms are reported in the text.

propriate epoch was re-subtracted to obtain a more uniform reference field thus minimizing the level shifts between the surveys. Finally edge matching along survey boundaries was achieved by applying a new multi-frequency suturing method (Johnson et al., 1999).

The new magnetic anomaly map furnishes the base for a series of other digital enhanced and filtered maps. In Fig. 2 we display an example of these maps. The total field anomaly map is superimposed upon the local maxima of horizontal gradient of pseudogravity (Cordell and Graunch, 1985).

Four main lineaments, L1, L2, L3 L4, (Fig. 2) are recognized along the main glaciers of the region and there is little evidence for NE trending coast parallel magnetic lineaments. A positive circular anomaly with the satellite peaks at Baker Rocks (BR) corresponds to the Mount Melbourne (MM) volcano itself. This anomaly is well distinct from the higher-frequency lower- amplitude anomalies of the Eisenhower Range (ER) and upper Deep Freeze Range, which are correlated to Jurassic Ferrar dolerite sills and subordinate subaerial basalt flows, and from the lower amplitude anomalies over Paleozoic Intrusives namely Mount Keinath (MK) and Teall Nunatak (TNk) in the Reeves Glacier. An upward continued version of the map (not displayed here) shows that the MM anomaly has a greater fall-off rate compared to the Random Hills (RH) anomaly likely indicating a shallower origin of the former. The latter anomaly is caused by a mostly buried Meander Intrusive which was detected also in ground magnetics (Bozzo and Meloni, 1992). Two N-S trends (T1 and T2) link the volcanic edifice to the pluton to the north (Fig. 2). High-frequency N-S trends are evident also at Cape Washington. The existence of high- frequency negative anomalies over the volcanic field is in good agreement with paleomagnetic data which show that some satellite bodies were formed in an epoch of reverse polarity (Lanza et al., 1991).

The complete Bouguer map (Fig. 3) including estimated ice-corrections and topographic corrections (2.67 SI units) was windowed from the regional map of Reitmayr (1997), which in this area also included data along the geodetic network installed on Mt. Melbourne (Cerrutti et al., 1992). The

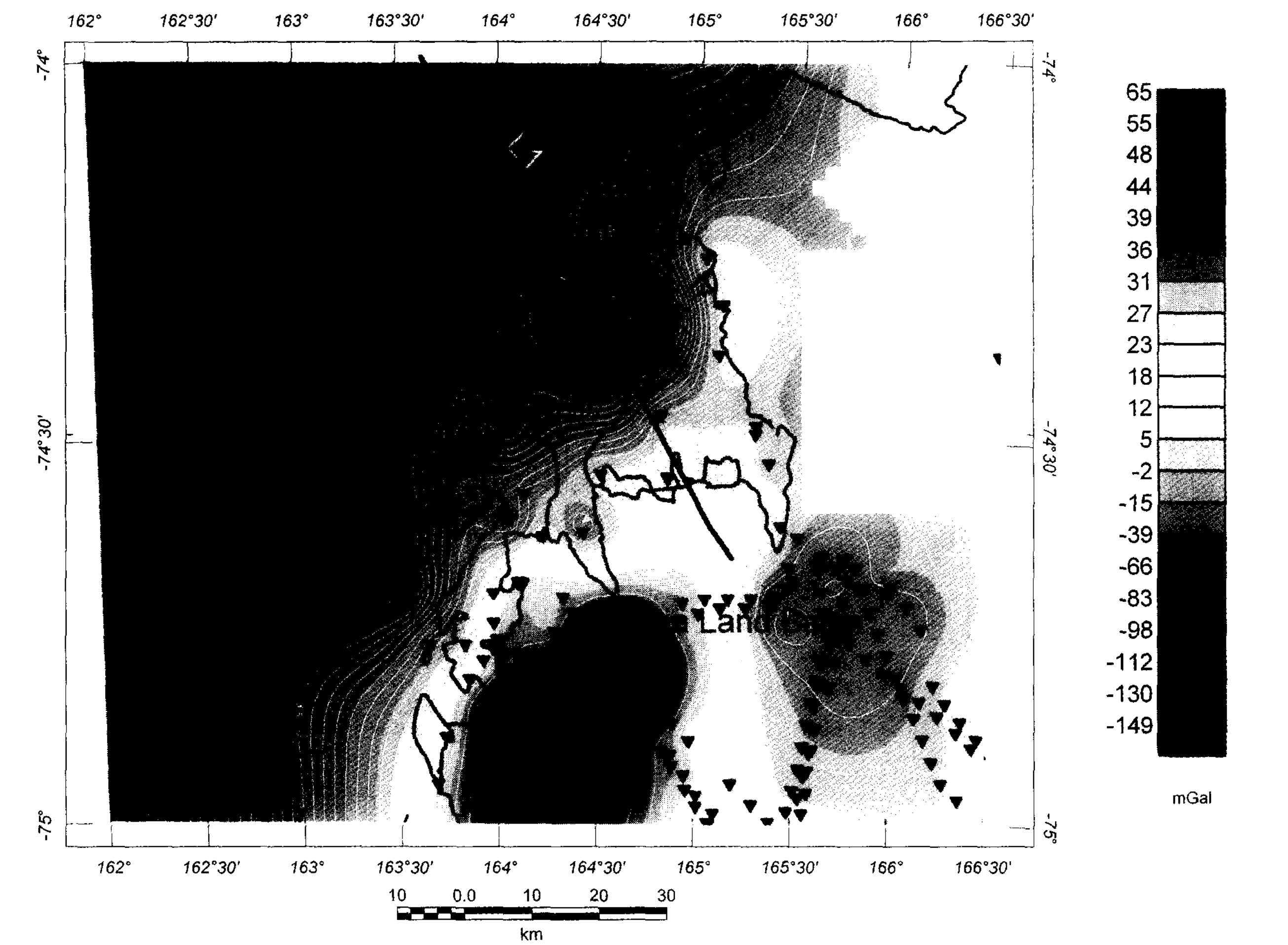

Fig. 3. Complete Bouguer anomaly map. Black triangles indicate the gravity station points. Some magnetic lineaments (L1, T1 and T2 in Fig.2) are also indicated for comparison.

map confirms the previously noted coast parallel gradient attributed to seismically constrained crustal thickening beneath the TAM rift shoulder and a more local negative round-shaped anomaly over MM itself. Relatively few stations define such a local anomaly. However new gravity points established during the 97/98 Italian Antarctic campaign (not included here) seem to confirm the presence of the anomaly itself. The low over MM is most likely due to low-density volcanics and volcano-clastic rock infill of the caldera similar for example to the Long Valley Caldera in Sierra Nevada with typical densities of 2.2 SI (C. Finn, personal comm.). It is also possible that part of the low could be related to a deeper sub-volcanic low-density body (hot magma chamber?) detected for example over several volcanoes in the Cascades (Williams and Finn, 1985).

Offshore there are two remarkable gravity features. One is a NNE gravity high close to Terra Nova Bay apparently matching the Drygalski Basin, which has been interpreted as being a recent pull-apart basin (Della Vedova and Pellis, 1994) characterized by higher heat flow (up to 110 $mW\ m^{-2}$) compared to the Terror Rift (89 $mW\ m^{-2}$). Upwarping of the mantle and/or dense crustal intrusions within the crust itself along the western flank of the Victoria Land Basin could explain the observed gravity anomaly. The other feature is a 30-km wide gravity low close to Cape Washington resembling the low over Mount Melbourne. Possibly this anomaly could also be due to a rift-related sub-volcanic intrusion.

5 Discussion of a new tectonic map

We compile and discuss a new tectonic map of the Mount Melbourne quadrangle (Fig. 4) by combining magnetic lineament analysis, gravity, geologic data and offshore seismic constraints. Recent tectonic interpretation based mainly upon offshore seismics (Salvini et al., 1997) calls for a transtensional opening of the N-S to NNW Terror Rift within the Victoria Land Basin due to right-lateral strike-slip deformation along NW-SE faults starting about 30 Ma ago and possibly still active. This interpretation is in good agreement with the magnetics offshore showing right- lateral offsets of the Cenozoic volcanic trends within the Victoria Land Basin and with preliminary interpretation of magnetic patterns to the north along the shoulders of the Rennick Graben (Fer-

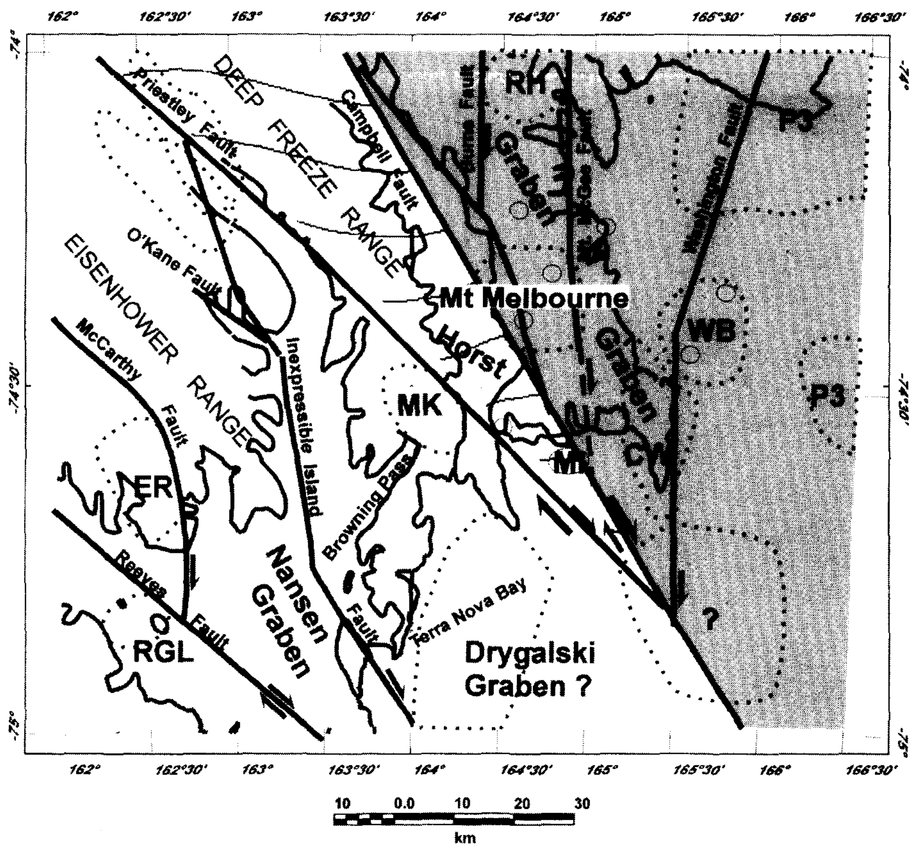

Fig. 4. New tectonic map of the Mount Melbourne quadrangle obtained by combining magnetic lineament analysis, gravity, geologic data and offshore seismic constraints.

raccioli and Bozzo, 1999; Bozzo et al., 1999). In analogy to these kinematic models over adjacent areas we interpret the NNW to NW magnetic lineaments within the MM quadrangle in terms of regional strike-slip faults. Offsets here are not clearly evident in the magnetics due to the regional character of the data and to the absence of clear magnetic markers on the two sides of the imaged faults.

In our model the Campbell Fault and the Priestley Fault (Salvini et al., 1997) converge and generate uplift of the Deep Freeze Range, which is consistent both with outcropping basement geology and apatite-fission track data (Balestrieri et al., 1997).

On the contrary, the Mt. Melbourne volcano would be located in a graben-like structure with shallow magnetic sources distributed along N-S trends, likely representing faults linking the volcanic field itself to an older alkaline intrusive complex underneath Random Hills. This region may be characterized by active(?) extension possibly generating present day local seismic events in particular along the eastern flank of the volcano (Bonaccorso et al., 1997) and subsidence of the volcano area in contrast to generalized uplift of the TAM as observed by Wörner and Viereck (1989). The more local N-S faults could act as transfer faults accommodating deformation along the major right-lateral strike-slip faults as predicted in the model of Salvini et al. (1997) offshore.

Apparently no major volumetrically significant magmatic activity occurred within the N-S Nansen graben (Skinner, 1989) strengthening the case for segmentation of the TAM across the Campbell and Priestley Faults (Ferraccioli and Bozzo, 1999).

Recent field work in the region (Rossetti and Storti, 1998) is in good agreement with the interpretation presented here since extensive brittle fault analysis is consistent with major strike- slip faults along the Campbell Glacier, Priestley Glacier, at Inexpressible Island and at Reeves Glacier. The proposed strike-slip tectonic framework could potentially be responsible also for inverse faulting which may thus not entirely be caused by local magma injection as previously inferred by Lanzafame and Villari (1991) but would be compatible with the proposed kinematic framework.

The regional gravity data presented here effectively images a recent pull-apart feature offshore characterized by high flow (Della Vedova and Pellis, 1994) and seismically constrained thin crust (18 km). Apparently, this structure terminates at the Campbell Fault. This gravity feature could well be linked with the proposed strike-slip tectonic framework. Also we imaged the presence of two NW-SE aligned low density (likely sub-volcanic) features associated to the Mount Melbourne volcanic field.

Though there has been general agreement based upon geologic and previous geophysical interpretations that the Mount Melbourne volcano is intimately related to the extensional tectonics in the Ross Sea region our study puts forward new constraints which support a strike- slip kinematic model for the region. The model appears to be more consistent with regional magnetics, gravity, seismics and field geology.

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