ACCEPTED FOR NEW ZEALAND MINERAL DEPOSITS MONOGRAPH

Revised 3D geometry of the platiniferous Hekeia Gabbro, Longwood Range, Southland

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ABSTRACT

The Hekeia Gabbro in the Longwood Range of Southland is prospective for platinum group element mineralisation. Recently acquired geological and isotopic data, combined with reinterpreted aeromagnetic data, provide new constraints on the three dimensional extent and internal structure of the gabbro. Direct observations of *in situ* subvertical igneous layering give confidence that most curvilinear aeromagnetic patterns are largely caused by macroscopic primary igneous layering. Steep magnetic gradients can be used to reliably define the areal limits of the Hekeia Gabbro and show that it extends to depths >1 km. Nd isotope ratios distinguish Hekeia Gabbro from younger gabbros and confirm the presence of at least two surface outcrops of Hekeia Gabbro a few km west of the main body. Hekeia Gabbro is interpreted to be part of a 5 km thick Late Permian lopolith that was subsequently deformed and intruded by other Late Permian and Triassic plutons.

KEY WORDS

Platinum, Permian, gabbro, Longwood Range, South Island

INTRODUCTION

The Longwood Range of Southland rises to over 800 m above sea level. It is underlain by Late Permian, Triassic and Jurassic plutons of the Median Batholith that intrude Early Permian volcanic and sedimentary rocks of the Takitimu Group of the Brook Street Terrane (Mortimer *et al*, 1999; Turnbull and Allibone, 2003; McCoy-West, Mortimer and Ireland, 2014; Craw, MacKenzie and Ashley, this volume). The gabbros of the Longwood Range have long been considered to be prospective for platinum group element (PGE) mineralisation because of reported rare PGE minerals in surface samples, anomalously high PGE assays of basement drillcore, and because of detrital platinum at Orepuki (Challis and Lauder, 1977; Cowden *et al*, 1990; Bluck, 1998; Ford, 1999; Ashley *et al*, 2012). The principal target for PGE mineralisation in the Longwood Range is the Late Permian Hekeia Gabbro (Mortimer *et al*, 1999; McCoy-West, Mortimer and Ireland, 2014) which is restricted to inland outcrops. More compositionally variable plutons, the Holly Burn Intrusives of Triassic and Jurassic age, are exposed on the coast between Colac Bay and Pahia Point (Figure 1). The last major exploration effort in the Longwoods was by Anzex who flew an aeromagnetic survey and completed four diamond drill holes totalling 2500 m (Bluck, 1998; Ford, 1999).

This paper summarises current knowledge of the spatial extent of the Hekeia Gabbro at the surface, and presents a magnetic model that helps define the size, depth, shape and internal structure of the pluton. New Nd isotopic data indicate that Hekeia Gabbro underlies at least two magnetic anomalies west of the main gabbro outcrop.

NEW FIELD OBSERVATIONS

Extensive forest below the bush line, thick soil and low relief mean that the quality and quantity of rock exposure is poor in the Longwood Range. Consequently there are large differences in geological interpretations (Mortimer *et al*, 2011 figure 4). Below the bush line, a 1-5 m thick mantle of colluvial bouldery clay smears and dilutes any soil or stream sediment anomalies and effectively insulates them from the bedrock. The present geological interpretation of the Longwood Range is shown in Figure 1.

The most studied part of the range is above the bush line near spot height 764 m (Figure 1) where Challis and Lauder (1977), Cowden *et al* (1990) and Rombouts (1994) presented moderately detailed geological maps. Even here, exposure is far from continuous and, while the rocks are fresh, solifluction processes have translated and tilted all but the largest rock tors. Thus it is uncertain how many of the c. 40 measurements of igneous layering and lamination by Rombouts (1994) are *in situ*. More reliable moderate westerly dips to igneous layering are inferred from nearby borehole intersections (Bluck, 1998; Ford, 1999; Ashley *et al*, 2012).

Hekeia Gabbro layering

The failure in August 2010 of a small dam high on the Longwood Range washed away trees, topsoil, colluvium and weathered rock, and created new exposures of fresh Hekeia Gabbro in a tributary of Ourawera Stream. The gabbro in several of these new exposures was both layered (changes in modal abundance of olivine, plagioclase, pyroxenes and hornblende) and laminated (preferred shape orientation of cumulate lath-shaped plagioclase crystals). The strike and dip of igneous lamination and layering in a c. 1 km long stream traverse in this part of the Longwood Range is typically 025/80ºE (the southern blue dip and strike symbol in Figure 1). Rare but consistent grading from hornblende-rich to plagioclase-rich gabbro indicates a magmatic ‘stratigraphic-top-to-the-west’ direction (Figure 2).

In a traverse in Cascade Stream on the eastern side of the Longwood Range, several new structural measurements were made of *in situ* gabbro. Here, igneous lamination and banding typically strike c. 140º, but vary in dip from 45ºNE to 80ºSW across a fault zone (the northern blue dip and strike symbol in Figure 1) which is marked by a small landslide and a cold ferruginous spring.

In both Ourawera and Cascade streams, the above mesoscopic strikes in igneous layering measured in the field match the macroscopic strike of long wavelength arcuate anomalies on the Anzex aeromagnetic map (Figure 3). It had previously been suspected that, based on the north-south extent of some lithologic units on the southern Longwood Tops (Rombouts, 1994), primary igneous layering was the cause of most of the magnetic fabric within the Hekeia Gabbro. This is confirmed by our new observations. We also confirm that NE-striking faults cut the gabbro and offset its eastern, hornfelsed contact.

Hand samples of the four main basement geological units in the Longwood Range (Brook Street Terrane metasedimentary rocks, Hekeia Gabbro, Pourakino Trondhjemite and Holly Burn Intrusives) have differing ranges of magnetic susceptibilities (Mortimer *et al*, 2012, figure 2). In particular the contrast between the high susceptibility gabbro and low susceptibility trondhjemite and metasedimentary rocks means that the edge of the gabbro pluton can be accurately mapped even though exposure is poor (the yellow dotted line in Figure 1). An exception is in the SW corner of the range, where field observations show that some gabbro is present east of the region of high positive magnetic anomaly.

MAGNETIC DATA AND MODELLING

Oriented samples of *in situ* Hekeia Gabbro were taken from several sites on the Longwood Range, and their natural remanent magnetisation (NRM) measured using a 2G Enterprises Cryogenic Magnetometer at the University of Otago’s Paleomagnetic Research Facility. See Mortimer *et al* (2012) for details of the methodology used.

Measured NRM directions and intensities are very variable for sites and samples supposedly from the same pluton. Mortimer *et al* (2012) attributed most of this variation to either a secondary magnetisation, possibly serpentinisation (Ashley *et al*, 2012), or to induced remanent magnetisation caused by lightning strikes on the crest of the range. For the southern half of the Longwood Range the inferred primary magnetisation has an approximate inclination of -70° and a declination of 200°. The reduced-to-pole (RTP) magnetic map of Figure 1B under this direction of magnetisation has maximum symmetry and maximum ratio between the amplitude of the positive and negative anomalies. Choosing the correct magnetisation direction for modelling is important because this has a significant impact on the interpreted geometry of the modelled bodies.

The RTP map (Figure 1) was used to make an apparent magnetisation map (Mortimer *et al*, 2012, figure 3B). Then, a 3D inversion of the apparent magnetisation map was made by dividing the subsurface into a set of voxels between the surface topography and a horizontal plane at depth (Caratori-Tontini, Cocchi and Carmisciano, 2006), in this case 1300 m below sea level. Among the large set of possible inversion models we chose one characterised by minimum magnetic energy, thus rejecting a large number of unrealistic models. However, solutions obtained in this way are commonly characterised by smooth variations of the magnetisation, and the resulting diffuse transitional boundaries make it difficult to recognise the real source geometry. As such, a further regularising term was used to produce a focused solution (Zhdanov, 2002). Figure 4 is a representation of the magnetisation of the 3D voxels which can be plotted as a discrete 3D approximation of the real magnetic source. This provides an alternative visualisation of the lateral extent of the magnetic Hekeia Gabbro and also shows its continuation at depth i.e. it is not rootless.

NEODYMIUM ISOTOPE DATA

The two main outcrops of Hekeia Gabbro outcrop at high elevations and are shown in purple on Figure 1A. These two bodies have been dated by U-Pb and Ar-Ar methods as Late Permian (245-260 Ma; Mortimer *et al*, 1999; McCoy-West, Mortimer and Ireland, 2014). They also have the geochemical and petrological character of arc cumulates (Rombouts, 1994; Mortimer *et al*, 1999, Ashley *et al*, 2012). Of particular note is that Hekeia Gabbro samples have very radiogenic age-corrected $^{143}Nd/^{144}Nd$ ratios ($\varepsilon Nd_T > 5$, see Figure 5), which distinguishes them as a Longwood Suite from a Darran Suite of younger arc-related gabbros and diorites of the Holly Burn Intrusives immediately to the east (Mortimer *et al*, 1999; Price *et al*, 2006).

Challis and Lauder (1977) and Cowden *et al* (1990) interpreted layered gabbros at Pahia Point as being part of the same gabbro as is now called the Hekeia Gabbro. However, subsequent isotopic dating by Price *et al* (2006) shows that the Pahia Gabbro is Jurassic, not Permian. As such it may not be as platinum prospective as the Hekeia Gabbro. However there are some prominent magnetic anomalies that lie east of the recognised Permian Hekeia Gabbro (eg western yellow dotted regions in Figure 1B) and field sampling shows that gabbros are responsible for the anomalies. In order to test whether these gabbros are Hekeia Gabbro *sensu stricto* or younger, unrelated gabbros we obtained Nd isotope data from two them (Table 1). Analytical methods for Nd isotopic analysis at the University of Otago follow procedures described in Weis *et al* (2006). The results show that, when compared with existing reference datasets (Figure 5), gabbro at these two western locations resemble Hekeia Gabbro rather than Darran Suite gabbros.

DISCUSSION AND CONCLUSIONS

Geometry

The areal extent of the Hekeia Gabbro, c. 90 km^2, as shown on the 1:250 000 geological map of Turnbull and Allibone (2003) is generally correct, although in places its contact against adjacent units should be revised by up to 1 km (Figure 1) to coincide with steep magnetic gradients on the RTP magnetic map. Further field checking is needed as, in places such as the SE corner of the range, gabbro occurs at the surface outside the strongly magnetic region. The contact metamorphic aureole of Hekeia Gabbro does not contain highly magnetic rocks. The pattern of the eastern edge of the gabbro being offset by NE-striking faults by up to 2 km is confirmed. Nd isotope measurements on some isolated Longwoods gabbro outcrops indicate that Hekeia Gabbro is not just restricted to the main two eastern outcrops but that some isolated western bodies are present, totally enclosed by Darran Suite plutons.

Field observations of modal igneous layering (Figure 2) confirm that the main curvilinear patterns on the magnetic map are caused by primary igneous layering. The arcuate magnetic fabric of the gabbro changes strike by c. 65º over a distance of <15 km (Figure 1B). The continuity of the macroscopic anomalies suggests that, for the most part, we are dealing with an intact part of the intrusion with a steeply-dipping and west-facing across-strike thickness of at least 5 km (Figure 3). This is all that is preserved; the northern and western edges of the gabbro have been intruded by younger plutons.

Magnetic modelling establishes that the Permian Hekeia Gabbro roots to at least 1 km below sea level (Figure 4). Bluck (1998), Naldrett (1999) and Naldrett and Ford (1998) proposed that the higher magnetic anomalies over the eastern part of the Hekeia Gabbro indicated the presence of stratigraphically-lower strongly-magnetic gabbros and peridotites, whereas stratigraphically higher, weakly-magnetic gabbros were present to the west. Certainly this could be true. An alternative interpretation, based on our modelling and the lack of correlation of hand sample magnetic susceptibility with aeromagnetic intensity (not shown), is that the local western weakening of the anomalies simply results from the feathering and thinning of the gabbro body to the west.

The preserved 5000 m thickness of igneous layering is comparable to that in many other platiniferous layered mafic intrusions (Table 2). Most igneous layering of this magnitude and extent is thought to have developed on the floor or roof of magma chambers and to have formed in a sub horizontal attitude (Naslund and McBirney, 1996).

History

The geological development of the Hekeia Gabbro is summarised in Figure 6. The host rocks to the gabbro are Early Permian Takitimu Group volcaniclastic sedimentary rocks. Hekeia Gabbro and related intrusions c. 60 km SE at Greenhills and Bluff are Late Permian to possibly earliest Triassic in age. U-Pb and Ar-Ar ages and Nd isotope ratios of the Pourakino Trondhjemite are within error of the Hekeia Gabbro and thus indicate a close, petrogenetic association of these rocks as a 245-265 Ma Longwood Suite, but rare field relationships indicate that trondhjemite dikes always cut gabbro, never vice versa.

On their western edges, the Longwood Suite gabbro and trondhjemite have been intruded by 235-200 Ma gabbros, diorites and granites of the Holly Burn Intrusives that are part of a New Zealand wide Darran Suite of I-type calcalkaline plutonic rocks. Folding of the Takitimu Group may have accompanied cross faulting of the Hekeia Gabbro margin and tilting of subhorizontal igneous layering to its now subvertical attitude (Figure 6) but the exact timing of, and connection between, these events is obscure. The original extent and shape of the Hekeia Gabbro has thus been strongly modified.

The geological, geochronological, isotopic and magnetic data and interpretations summarised in this paper provide a clearer understanding of various aspects of the platiniferous Hekeia Gabbro in the Longwood Range. Progress since the summary by Christie *et al* (2006) includes improved definition of the surficial extent of the gabbro body, reliable confirmation of its Late Permian age and isotopically primitive character, ground-truthing of the match of curvilinear aeromagnetic anomalies with now steeply-dipping primary igneous layering, and modelling of the gabbro as part of a tilted lopolith with substantial vertical extent. Collectively these advances improve targeting of this poorly exposed gabbro for platinum explorers.

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FIGURE CAPTIONS

FIG 1 – A. Simplified geological outline of the Longwood Range after Turnbull and Allibone (2003). 100 m contours; thin white dotted line is edge of bush. Thicker dotted yellow line is revised position of the limits of Hekeia Gabbro, manually traced and transferred from the steep magnetic gradient in Figure 1B. B. Reduced to pole (RTP) magnetic map (same area as A); magnetic data from Bluck (1998), reprocessed. Coordinates are NZTM2000.

FIG 2 – Field photograph looking down on *in situ* subvertically-dipping modal igneous layering in Ourawera Stream. Pencil tip points west in the "stratigraphic up" direction.

FIG 3 – Interpretation of the km-scale internal layering of the main mass of Hekeia Gabbro. Most of the western and northern edge of gabbro has been intruded by younger plutons. See Figure 1B for location.

FIG 4 – Three-dimensional magnetic inversion model of the 16 x 12 km area of Figure 1B. Z= elevation relative to sea level.

FIG 5 – Nd isotope data for plutonic rocks from the area of Figure 1 and from Brook Street Terrane volcanic and sedimentary rocks. Reference data from Frost and Coombs (1989), Mortimer *et al* (1999), Tulloch *et al* (1999), Adams *et al* (2005), Price *et al* (2006) and Nebel *et al* (2007). New data are represented by two digit numbers which relate to the last two digits of the P numbers in Table 1.

FIG 6 – Schematic geological development of the Longwood Range showing the intrusional and deformational history of the platiniferous Hekeia Gabbro lopolith and later plutons. Not to scale.

TABLE CAPTIONS

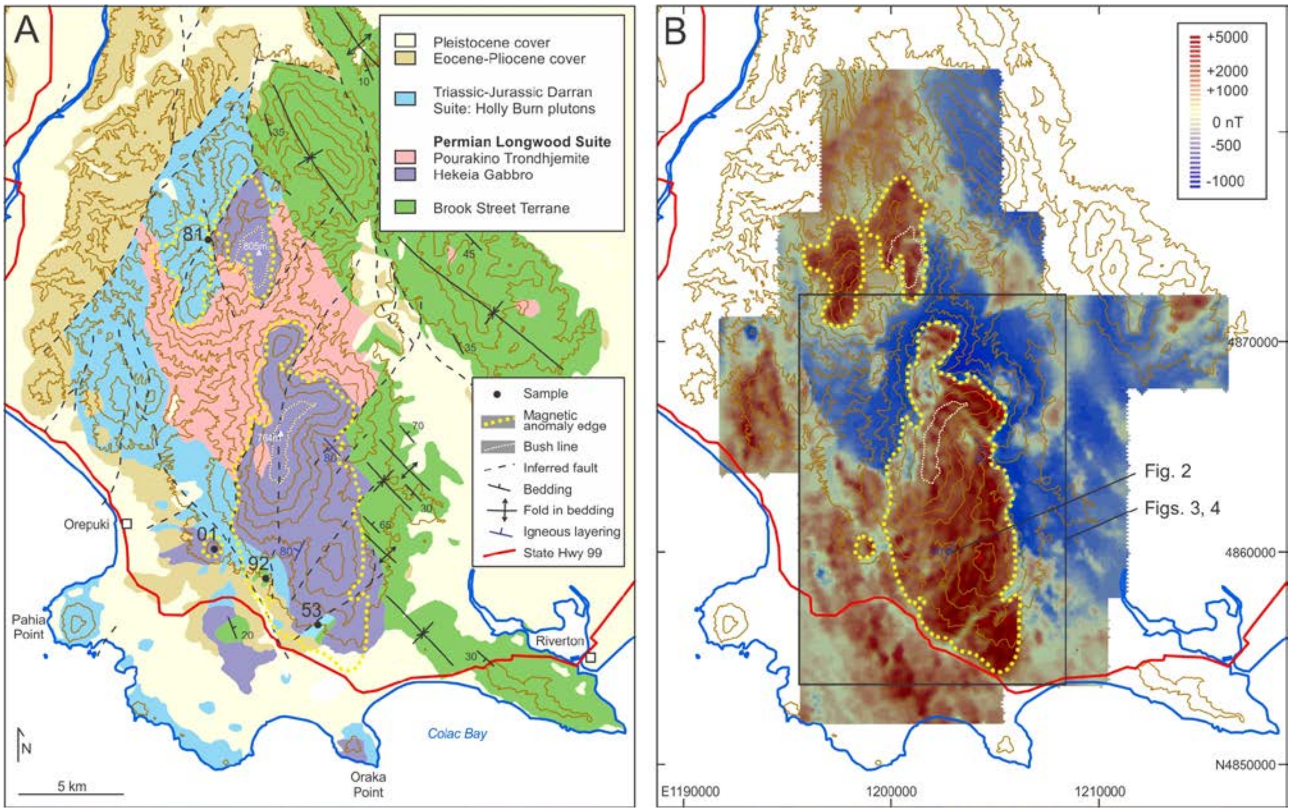
TABLE 1

Sm-Nd isotope data for four Longwood Range gabbros.

TABLE 2

Approximate areas of selected platiniferous mafic intrusions and the approximate maximum reported stratigraphic thickness of igneous layering.

FIGURES



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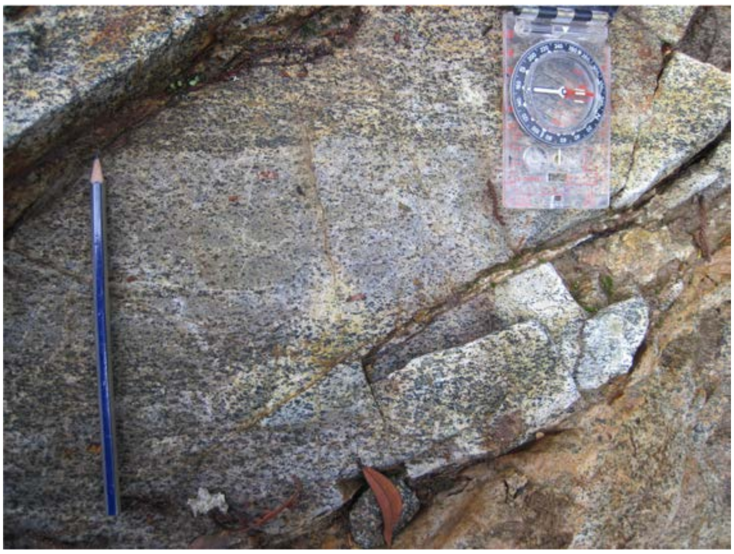

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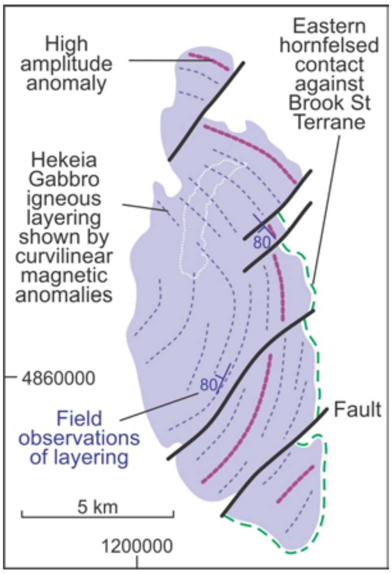

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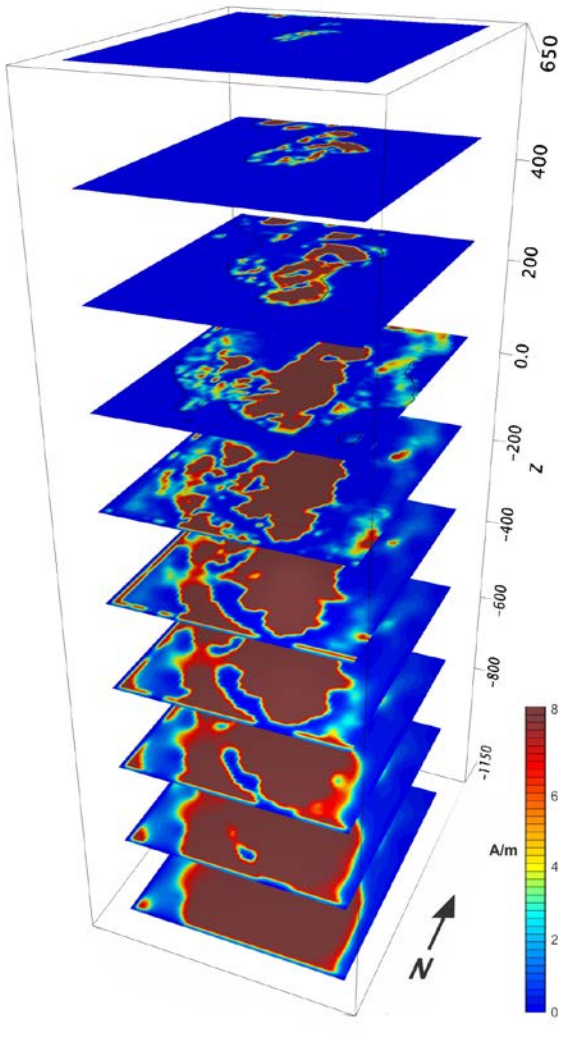

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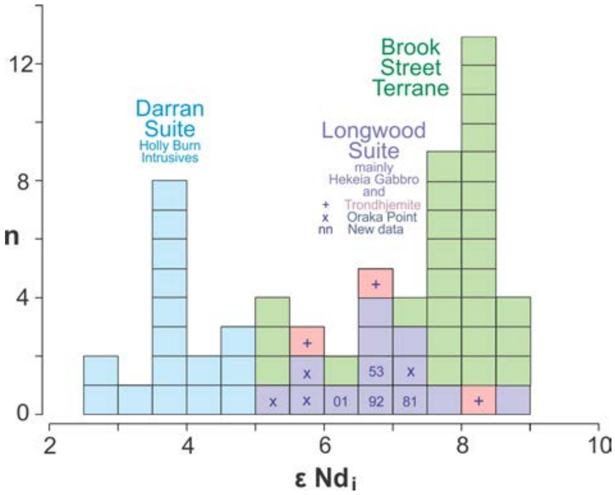

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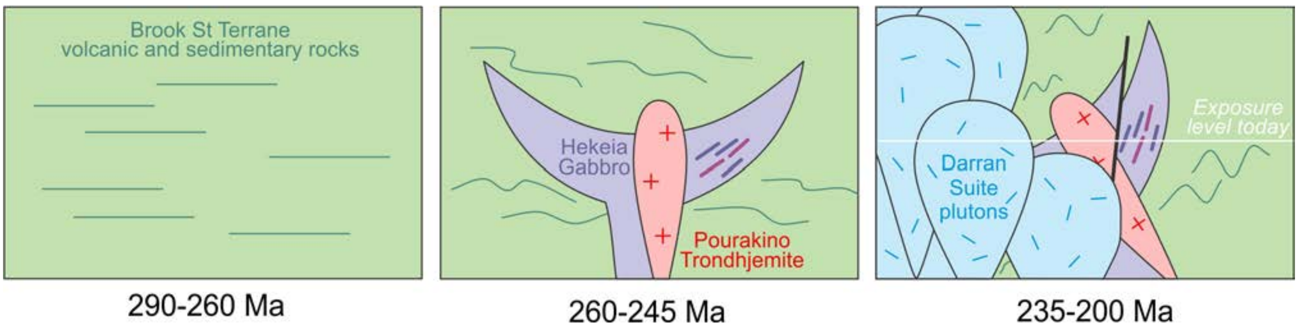

FIG 6 – Schematic geological development of the Longwood Range showing the intrusion and deformation history of the platiniferous Hekeia Gabbro and later plutons. Not to scale.

TABLES

TABLE 1

Sm-Nd isotope data for four Longwood Range gabbros.

Sample	**Location**	**Sm (ppm)**	**Nd (ppm)**	**$^{143}Nd/^{144}Nd$**	**$\varepsilon Nd_{(0Ma)}$**	**$^{147}Sm/^{144}Nd$**	**$^{143}Nd/^{144}Nd_{(250Ma)}$**	**$\varepsilon Nd_{(250Ma)}$**
P08053	Ports Race	1.55	5.23	0.512942±06	5.9	0.1784	0.512650	6.5
P59681	Boundary Creek	3.79	12.9	0.512969±08	6.5	0.1760	0.512681	7.1
P81192	Ourawera Stream	3.11	9.05	0.513008±07	7.2	0.2068	0.512669	6.9
P81201	Round Hill	0.34	1.14	0.512934±12	5.8	0.1795	0.512641	6.3

Note: CHUR values used $^{143}Nd/^{144}Nd$ today = 0.512638, $^{147}Sm/^{144}Nd$ = 0.1967, $\lambda^{147}Sm = 6.54 \times 10^{-12}$.

For sample locations and additional analytical data see Petlab database http://pet.gns.cri.nz

TABLE 2

Areal extent and maximum reported straigraphic thickness of selected platiniferous mafic intrusions.

Intrusion	**Area (km^2)**	**Thickness (m)**	**Age**
Bushveld, South Africa	65 000	7300	Precambrian
Duluth, Minnesota, USA	5000	1200	Precambrian
Great Dyke, Zimbabwe	5000	3000	Precambrian
Windimurra, Australia	2300	13 000	Precambrian
Stillwater, Montana, USA	400	52 800	Precambrian
Laperouse, Alaska, USA	250	6000	Cenozoic
Skaergaard, Greenland	100	2500	Cenozoic
Hekeia, New Zealand	80	5000	Permian
Penikat, Finland	70	2700	Precambrian
Noril'sk/Talnakh, Russia	60	3500	Permian