Geophysical identification and characterization of mafic-ultramafic intrusions in
plume centre regions

By

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Abstract

Gravity and magnetic data from the EGM2008 and EMAG2 datasets are used for a global study of geophysical anomalies in LIP plume centre regions with the goal of identifying mafic-ultramafic intrusions linked to those LIPs. Geophysical anomalies within eighteen LIPs are investigated. Four of these LIPs are selected for detailed modelling: the Mackenzie, High-Arctic, Kunene-Kibaran, and Deccan LIPs.

Modelling supports that these anomalies are produced by large (radius >30 km) and generally deep-seated crustal intrusions, with densities consistent with mafic-ultramafic rock and magnetic susceptibilities consistent with serpentinized ultramafic rock. Modelling also indicates that these values remain consistent within a LIP, particularly regarding density and depth. Lastly, we recognize three types of spatial distributions for intrusions in plume centre regions: 1) intrusions that circumscribe the plume centre emplaced along circular fault systems, 2) intrusions emplaced along rifts, in some cases rifts that converge towards the plume centre, and 3) single/unclassified intrusions.

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Table of Contents

Abstract	i
Acknowledgments	ii
1 Introduction	1
1.1 Large Igneous Provinces	1
1.2 Earth Modelling using Geophysical Methods	4
1.3 Research Objectives	5
2 Background Information	8
2.1 LIP Plumbing Systems	8
2.1.1 Mafic Dyke Swarms	10
2.1.2 Sill-like, Dyke-like and Funnel-Shaped Layered Intrusions	13
2.1.3 Sill Complexes.....	14
2.1.4 Magmatic Underplating	14
2.1.5 LIP Fragmentation	18
2.2 Mineral Potential in Plume Centre Regions.....	19
2.3 Economic Considerations	23
3 Theory: Potential Field Methods in Exploration Geophysics.....	25
3.1.1 Introduction to Gravity Methods	25
3.1.2 Gravitational Acceleration.....	26

3.1.3	Gravity Corrections.....	27
3.2	Magnetic Methods	30
3.2.1	Introduction to Magnetic Methods.....	30
3.2.2	Magnetic Principles	32
3.2.3	Magnetic Corrections	34
3.3	Potential Field Methods	35
3.4	Rock Properties.....	38
4	Project Data Sets	40
4.1	EGM2008.....	40
4.2	EMAG2.....	43
4.3	CRUST1.0	45
5	Modelling Software and Methodology.....	46
6	Results	55
6.1	Reconnaissance Survey of Plume Centre Regions	55
6.1.1	Candidates.....	58
6.2	Mackenzie LIP (1270 Ma), Northwest Territories, Canada	74
6.2.1	Geological Overview	74
6.2.2	Geophysics in the Mackenzie Plume Centre Region	80
6.2.3	Modelling	87

6.2.4	Discussion.....	96
6.3	Kunene-Kibaran LIP (c. 1380 Ma), East Africa.....	102
6.3.1	Geology of the Lake Victoria Region	102
6.3.2	Geophysics in the Lake Victoria Region.....	110
6.3.3	Modelling	118
6.3.4	Discussion.....	125
6.4	Deccan LIP (66 Ma), Western India	132
6.4.1	Geological Overview.....	132
6.4.2	Geophysics in the Deccan Plume Centre Region.....	140
6.4.3	Modelling	153
6.4.4	Discussion.....	160
6.5	High Arctic LIP (130 to 80 Ma), Arctic Canada	164
6.5.1	Geological Overview.....	164
6.5.2	Geophysics and Modelling	170
6.5.3	Discussion.....	176
6.6	Summary.....	179
7	Discussion.....	179
7.1	General Observations from Modelling	182
7.2	Distribution of Intrusions in Plume Centre Regions.....	186

7.2.1	Intrusions with Circumferential Distributions	186
7.2.2	Intrusions emplaced along Linear Rift Systems	189
7.2.3	Unclassified Intrusions	190
7.3	Final Comments and Modelling Limitations	194
8	Conclusion and Recommendations for Future Work	197
9	References.....	201

LIST OF FIGURES

Figure 1: The 1270 Ma Mackenzie LIP, Canada	3
Figure 2: General cross section diagram of LIP plumbing systems	9
Figure 3: Characteristic geometries of regional-scale dyke swarms	12
Figure 4: Cross-section model of the 1115-1085 Ma Keweenawan LIP	16
Figure 5: Magmatic underplating models from seismic data	17
Figure 6: The general distribution of major Ni-Cu-PGE deposits within LIPs.....	22
Figure 7: Limiting depth estimates from gradient to amplitude ratios.....	36
Figure 8: Global map of EGM2008 data availability	41
Figure 9: Standard deviations map for EGM2008	42
Figure 10: Global 2 arc minute Earth Magnetic Anomaly Grid (EMAG2).....	44
Figure 11: Methodology steps.....	52
Figure 12: Global distribution of LIPs investigated.....	63
Figure 13: Bouguer anomaly map the western Deccan Traps, India	68
Figure 14: Magnetic anomaly map near the HALIP plume centre, Arctic Canada	69
Figure 15: Bouguer anomaly map of the West Africa component of the Paraná-Etendeka LIP	70
Figure 16: Bouguer anomaly map of the Mackenzie and Franklin LIP plume centre regions	71
Figure 17: Bouguer anomaly map of the Kunene-Kibaran LIP, East Africa, near Lake Victoria	72
Figure 18: Bouguer anomaly map of the Cuddapah basin in the Dharwar craton, India.....	73
Figure 19: Generalized map of the 1270 Ma Mackenzie event, Northwest Territories, Canada ...	77
Figure 20: Bedrock geology map of Victoria Isl., Banks Isl., and the northern Canadian Arctic Mainland	78

Figure 21: Schematic diagram of the Muskox intrusion	79
Figure 22: Bouguer anomaly map of the Mackenzie plume centre with modelling profile lines...	83
Figure 23: Geological map in the vicinity of the Mackenzie plume centre.....	84
Figure 24: Map of the the Amundsen Embayment.....	85
Figure 25: Magnetic anomaly map near the Mackenzie plume centre	86
Figure 26: Mackenzie profile model along line A-A'	89
Figure 27: Mackenzie profile model along line B-B'	91
Figure 28: Mackenzie profile model along line C-C'	94
Figure 29: Mackenzie profile model along line D-D'	95
Figure 30: Schematic 3D model of the Mackenzie mafic bodies.....	99
Figure 31: Model for the formation of the Mackenzie LIP	100
Figure 32: Additional targets identified from gravity data	101
Figure 33: General geology of the Greater Congo Craton (GCC)	106
Figure 34: Geological map of the Lake Victoria region	107
Figure 35: Geology of Uganda	108
Figure 36: General of Tanzania.....	109
Figure 37: Bouguer anomaly map in the Lake Victoria region.....	113
Figure 38: Uganda geology with gravity contour lines	114
Figure 39: Tanzania geology with gravity contour lines.....	115
Figure 40: Magnetic anomaly map in the Lake Victoria region before reduction to the pole	116
Figure 41: Magnetic anomaly map in the Lake Victoria region after reduction to the pole.....	117
Figure 42: Curie point depth estimates for central southern Kenya Rift.	120

Figure 43: Kunene-Kibaran profile model along line A-A'	121
Figure 44: Kunene-Kibaran profile model 1 along line B-B'	123
Figure 45: Kunene-Kibaran profile model 2 along line B-B'	124
Figure 46: Plume origin for the Kunene-Kibaran LIP	130
Figure 47: Schematic diagram for the formation of the LVDS and associated intrusions	137
Figure 48: Geology and tectonic map of the Indian Shield and the Deccan Traps.....	137
Figure 49: Age distribution of the Deccan Traps	138
Figure 50: Deccan–Réunion hot spot trail.	139
Figure 51: Bouguer anomaly map of the Deccan traps	144
Figure 52: Bouguer anomaly map in Saurashtra	146
Figure 53: Geological map of the western Deccan LIP in Saurashtra, India	147
Figure 54: Magnetic anomaly map of western Saurashtra.....	148
Figure 55: Bouguer anomaly map of the western Deccan Traps from EGM2008.....	150
Figure 56: Magnetic anomaly map reduced to the pole.	151
Figure 57: Seismic anomaly map, India.....	152
Figure 58: Deccan model 1 along line A-A'	156
Figure 59: Deccan model 2 along line A-A'	157
Figure 60: Deccan model 3 along line A-A'	158
Figure 61: Postulated Deccan plume centre location	163
Figure 62: Generalized map of the High Arctic Large Igneous Province	167
Figure 63: Bedrock geology map of Ellesmere and Axel Heiberg Islands	168
Figure 64: Comparison of the HALIP magnetic anomaly with bedrock geology.....	169

Figure 65: Magnetic and gravity anomaly maps on western Ellesmere Island	171
Figure 66: HALIP model 1 along line A-A'	173
Figure 67: HALIP model 2 along line A-A'	175
Figure 68: Spatial distribution of layered intrusions in plume centre regions.....	193

LIST OF TABLES

Table 1: General Thesis Goals.....	7
Table 2: Modelling Goals	7
Table 3: Major Ni-Cu-PGE deposits linked with LIPs	21
Table 4: Depth estimates.....	37
Table 5: Common Rock Density values	39
Table 6: Common Rock Susceptibility values.	39
Table 7: Summary of geophysical anomalies in 18 plume centre regions.....	64
Table 8. Modelling results summary from the Bhattacharji et al. (2004) study.....	145
Table 9. Modelling results summary from the Chandrasekhar et al. (2002) study	149
Table 10: Modelling results summary from this study.....	159
Table 11: Summary table from modelling in four plume centre regions.....	179

1 Introduction

1.1 Large Igneous Provinces

A Large Igneous Province (LIP) is a primarily “mafic (+ultramafic) magmatic province with an aerial extent $> 0.1 \text{ Mkm}^2$ and igneous volume $> 0.1 \text{ Mkm}^3$, that has intraplate characteristics, and is emplaced in a short duration pulse or multiple pulses (less than 1-5 Ma), with a maximum duration of $< c. 50 \text{ Ma}$ ” (Ernst, 2014a). LIPs are commonly linked with continental rifting and breakup, major climate shifts, silicic magmatism, as well as various types of ore deposits (e.g., Ernst et al., 2005). Recent years have witnessed an increase in the understanding of their role in the genesis of mineral deposits (e.g. Ni-Cu-PGEs), hydrocarbon and ground-water resources, and as a result, this has led to an increase in the understanding of their economic significance and their role in the mining industry (e.g., Ernst and Jowitt, 2013; Ernst, 2014a).

The origin of LIPs is often debated. Many LIPs are commonly attributed to the arrival of a mantle plume at the base of the lithosphere (e.g., Richards et al., 1989; White and McKenzie, 1995; Eldholm and Coffin, 2000; Hooper, 2000; Campbell, 2005; Ernst et al., 2005; Saunders et al., 2005; Campbell and Kerr, 2007; Hooper et al., 2007). Evidence for the existence of mantle plumes includes the formation of hot spot tracks, such as the Hawaiian volcanic chain, where there is a clear increase in age with distance from the active volcanoes Kilauea and Mauna Loa that cannot be explained by normal plate tectonic processes (Morgan, 1972a, b; Campbell, 2005; Tarduno, 2007)

Even so, not all LIPs have a clear connection with a mantle plume origin, suggesting that more than one model may be required to explain the formation of all LIPs. Alternatives to the plume model include normal plate tectonic processes and bolide impacts, among others (e.g., Jones et al.

2002, Foulger et al., 2005; Sheth, 2005; Foulger and Jurdy, 2007; Foulger, 2007; 2010; 2012; Anderson, 2013; Smith, 2013). For the purposes of this thesis, only LIPs for which a mantle plume origin is the most widely accepted origin in its formation are considered.

It is generally difficult to recognize the full extent of a LIP since these are composed of both intrusive and extrusive components which may be partially or, in the case of the extrusive component, entirely eroded, making total magma volume estimates difficult (e.g., Ernst et al., 2005). In younger LIPs of Mesozoic and Cenozoic ages, continental flood basalts are commonly preserved and play an important role in LIP identification. Older LIPs tend to be deeply eroded, in which case they may be identified by their plumbing systems that often occur in the form of giant radiating dyke swarms, sill provinces, and layered intrusions (e.g., Ernst et al. 2005). In many cases, LIPs are also associated with regional-scale domal uplift (e.g., Morgan, 1971; Griffiths and Campbell, 1991; Farnetani and Richards, 1994; Rainbird and Ernst, 2001; Şengör, 2001; Saunders et al., 2007), which has an important role in the formation of fractures in the crust that facilitate the magma's ascent to the surface, and which can lead to the formation of giant radiating dyke swarms that can carry magma laterally away from the plume centre region for up to more than 2000 km (e.g., Baragar et al., 1996). One of the most impressive examples is the 1270 Ma Mackenzie giant radiating dyke swarm located in the Northwest Territories, Canada (Figure 1), that covers nearly 3 Mkm² of the Canadian Shield. In this example, the plume centre is identified at the focus of the giant radiating dyke swarm (star).

Figure 1: The 1270 Ma Mackenzie LIP, Canada. Most prominent is the giant radiating dyke swarm (red lines) that spans in excess of 2000 km across the Canadian Shield. The plume centre is at the focus of the swarm (red star), located on Victoria Island in northern Canada. After Buchan et al. (2010).

1.2 Earth Modelling using Geophysical Methods

Geophysics is a discipline that seeks to obtain information about the subsurface indirectly by detecting variations in rock properties (e.g., Telford et al., 1990). Given that the majority of a LIP's components are not exposed at the surface, their detection and characterization are reliant on geophysical methods.

This thesis focuses primarily on the gravity and magnetic geophysical methods, which measure the Earth's gravitational acceleration and the intensity of the Earth's magnetic field, and provide insight into the density and magnetic susceptibility properties of the rocks in the subsurface, respectively. These in turn are used to identify rock compositions. The availability of regional-scale gravity and magnetic anomaly data has provided an opportunity to conduct a global survey of geophysical anomalies in plume centre regions. Modelling incorporates gravity and magnetic data from the EGM2008 and EMAG2 datasets, along with information from seismic data and geological maps to constrain the properties and dimensions of the layered intrusions investigated herein.

1.3 Research Objectives

The link between LIPs and Ni-Cu-PGE mineralization has become well established over recent years, particularly in their relation to mafic-ultramafic layered intrusions (e.g. Naldrett, 1997, 2010a, b; Pirajno, 2000; Schissel and Smail, 2001; Eckstrand and Hulbert, 2007; Sluzhenikin, 2011; Song et al., 2011). Current frontiers in LIP research include better characterizing LIPs in terms of their plumbing system geometries and, in consideration of Ni-Cu-PGEs, better understanding the distribution of mafic-ultramafic intrusions in plume centre regions (e.g., Ernst and Jowitt, 2013).

This thesis focuses on the plumbing system of LIPs, with an emphasis on mafic-ultramafic layered intrusions that are a large component of the plumbing system. A geophysical approach is used to identify and characterize intrusions in plume centre regions of LIPs (Blanchard et al., 2014, 2015), where intrusions can be more reliably linked with an associated LIP due to their proximity to the plume centre and where economic potential is greatest. A global survey is conducted across 18 LIPs in search of geophysical anomalies that are good candidates for layered intrusions linked with a LIP. The best candidates within four plume centre regions are then modelled in order to provide density and magnetic susceptibility estimates, as well as providing insight into their volume, shape, and depth beneath the surface (see Table 1 and 2).

The intrusions identified in this study are observed at regional scales and as a result are more likely to be located deep within the Earth's crust. Therefore, the intrusions we seek to identify in the present study are not exploration targets, but their presence has important implications for related near-surface ore deposits, as these are often sourced directly from deeper components of the

plumbing system (e.g., the Muskox intrusion linked with the Mackenzie LIP, North America; Baragar et al., 1996).

For this study, gravity data collected during the Gravity Recovery and Climate Experiment (GRACE) is used in conjunction with data provided by the National Geospatial-Intelligence Agency (NGA) leading to the formation of the 2008 Earth Gravitational Model (EGM2008), and the Earth Magnetic Anomaly Grid (EMAG2) assembled from CHAMP (Challenging Minisatellite Payload) satellite, ship and airborne measurements. Geophysical modelling is achieved through forward modelling and inversion in Geosoft's Oasis Montaj profile modelling software GM-SYS available at www.geosoft.com. The final product is cross section interpretations of the subsurface geology across 11 geophysical anomalies in four plume centre regions.

Table 1: General Thesis Goals

General Goals	Broad Technique	Motives
Identify mafic-ultramafic intrusions linked with LIPs	Intrusions are identified using gravity and magnetic anomaly data within 18 plume centre regions.	Layered intrusions identified through geophysical methods can directly or indirectly provide new targets for exploration, and can provide insight into to plumbing system geometry of LIPs.
Characterize the intrusions	Joint modelling of gravity and magnetic data, while incorporating seismic data with known and inferred geology as constraints.	Modelling can provide depth, volume, shape and composition estimates. (Table 2)
Classify LIPs in terms of the distribution of layered intrusion with respect to the plume centre regions	Note spatial distribution of intrusions with respect to plume centres and associated rift systems.	The setting of intrusions (e.g. along a rift) provides insight into how the intrusions were emplaced and additionally advances the current understanding of how magma is transported through LIP plumbing systems The proximity of an intrusion to the plume centre also aids in correlating an intrusion with a LIP.

Table 2: Modelling Goals

Modelling Goals	Motives
Depth estimates	First order depth estimates provide insight into the accessibility of the intrusions. We are also interested in how layered intrusions tend to be emplaced within LIPs (i.e. whether they are generally positioned at the lowest levels of the plumbing system or near the paleo-surface). Not that in younger LIPs, where less erosion is likely to have occurred, estimates of the initial emplacement depth are more reliable.
Volume estimates	The total volume of LIP magmatism is difficult to constrain. Estimating the dimensions of major components of the plumbing system can aid in estimate the amount of magma that is distributed into the crust during LIP magmatism.
Density and magnetic susceptibility estimates	Density and magnetic susceptibility estimates are useful for identifying the composition of the intrusive rocks.
Intrusion shape	The emplacement geometry of the intrusions (for example, dyke-like vs. sill-like intrusions) can provide insight on how the intrusions were emplaced.

2 Background Information

2.1 LIP Plumbing Systems

The plumbing system acts as the magma transport system for the LIP and carries magma from underlying mantle sources into the lithosphere, distributing it into the crust and lithospheric mantle as intrusions and onto the surface as flood basalts (Ernst, 2014a). The plumbing system is composed of mafic dyke swarms, sill complexes, mafic-ultramafic intrusions and magmatic underplating (Figure 2), (Ernst, 2014a). The following is a brief description of LIP plumbing system components, with a focus on layered intrusions.

Figure 2: General cross section diagram showing the role of mantle plumes in the formation of LIP plumbing systems, and the general stratigraphy of LIP plumbing systems. Modified from Richards et al., (2015).

2.1.1 Mafic Dyke Swarms

When the plumbing system has been exposed through erosional processes, it is common to observe coeval dolerite dykes that in some cases can be individually traced up to 1000 km (Eyal and Eyal, 1987). Often, these are situated within basement rocks and are observed as dyke swarms with linear, radiating or arcuate geometries. Individual dyke widths tend to be roughly 10 to 40 m on average (Ernst, 2014a), however known dyke widths can be up to several hundred kilometers in width, such as the 600 m dykes belonging to the Great Dyke of Carolina linked with the Central Atlantic Magmatic Province (CAMP) event (Nomade et al., 2007).

2.1.1.1 Regional-Scale Dyke Swarms

Regional-scale dyke swarms are common within LIPs and can typically be divided into six main types based on observed swarms worldwide (Figure 3; Ernst and Buchan, 2001b). Giant radiating dyke swarms of Types I and II converge to a single point inferred to mark the location of the plume centre either as a continuous swarm or as discontinuous fanning subswarms with dyke-poor regions, respectively. These can, in certain cases, fan out over 100° such as is observed with the Mackenzie giant radiating dyke swarm, North America (Baragar et al., 1996).

Often, LIPs are linked with triple junction rifting. Dykes swarms of Type III, in which subswarms of parallel dykes radiate from a single point, are commonly observed where a triple junction has occurred. Types IV and V are sub parallel dykes distributed over broad and narrow zones, respectively. The final Type VI is a giant arcuate dyke swarm that can be primary and due to a swing in the stress pattern during emplacement, due to secondary deformation, or can potentially represent part of a primary circumferential swarm (Ernst and Buchan, 1998; Ernst et al., 2014).

Dyke swarms make up a large component of the magma transport system. From these systems, magma is further distributed into the crust laterally as sills or emplaced as intrusions in the crust (e.g., Ernst and Buchan, 1997). Consequently, it is anticipated that many intrusions emplaced during LIP magmatism will tend to follow the same geometrical patterns of Types I to VI. For example, intrusions may be emplaced linearly along a rift arm, or in a circular pattern along a circumferential dyke swarm.

Figure 3: Characteristic geometries of observed regional-scale dyke swarms divided into six types. Types I and II show continuous and discontinuous fanning patterns, the latter being divided into dyke subswarms. Type III shows sub parallel dyke subswarms radiating from a single point (triple junction rifting). Types IV and V are sub parallel dykes distributed over broad and narrow zones, respectively, and Type VI is an arcuate pattern of dykes. From Ernst and Buchan (2001).

2.1.2 Sill-like, Dyke-like and Funnel-Shaped Layered Intrusions

Major ore deposits, particularly Ni-Cu-PGE-types, are commonly hosted in layered mafic-ultramafic intrusions linked with LIPs (e.g., Naldrett, 1997, 2010a, b; Pirajno, 2000; Schissel and Smail, 2001; Eckstrand and Hulbert, 2007; Sluzhenikin, 2011; Song et al., 2011). Intrusions belonging to LIP plumbing systems tend to be large enough to exhibit internal differentiation and are typically composed of lower ultramafic and upper tholeiitic components, thus making them ideal candidates for the formation of Ni-Cu-PGE deposits. These types of deposits are extremely important to the mining industry, and understanding their relation to the plumbing system as an entirety is the key to understanding their economic potential (e.g., Naldrett, 1999; Ernst, 2007).

Layered intrusions are classified as being sill-like or dyke-like (Hatton and von Gruenewaldt, 1990), with an additional sub classification of funnel- (or Y-) shaped intrusions (Hall, 1996; Ernst, 2014a). Sill-like intrusions have a horizontal sheet-like geometry with a large length to thickness ratio (e.g., Ashwal, 1993). For instance, the Bushveld Complex of South Africa contains the world's largest layered intrusion (the Rustenburg Layered Suite) that has a surface area of roughly 400 km by 300 km and an approximate thickness of 7 km to 8 km (Cawthorn, 1996; Barnes and Maier, 2002). On the other hand, dyke-like intrusions have a vertical sheet-like geometry with dyke widths that are much greater than ordinary dolerite dykes (e.g., 1 km for the Great Dyke of Zimbabwe; Podmore and Wilson 1987).

Dyke-like intrusions are commonly emplaced at the boundary between basement and supracrustal sequences, and may themselves produce sill-like layered intrusions along the basement-crust interface (e.g., Ernst, 2014a). In this sense, intrusions can be both dyke-like and sill-like along different sections of the intrusion. An excellent example is the Koillismaa Layered Igneous

Complex (KLIC) linked with the c. 2450 – 2500 Baltic LIP, where the eastern Näränkävåara body is trough-shaped and represents the exposed part of a feeder intrusion with steeply-dipping contacts, while the Western Intrusion is sill-like with a great aerial extent and thinning to only a few kilometers thick (Iljina et al., 2001).

2.1.3 Sill Complexes

Dolerite sill complexes are commonly emplaced into sedimentary successions as saucer-shaped intrusions (e.g., Svensen et al., 2012), though seismic imaging also indicates their presence in the underlying basement rock (e.g., Welford and Clowes, 2004). Individual sills can range in thickness from less than a meter to hundreds of meters and can extend for a few tens of kilometers, generally increasing in diameter with depth (Galland et al., 2009; Ernst, 2014a).

2.1.4 Magmatic Underplating

A significant component of the magma that reaches the Earth's crust during LIP magmatism does not reach the surface and instead solidifies at the base of the crust, or as intrusions in the lower crust depending on the relative density of magma and crustal material (Cox, 1980, 1993; Furlong and Fountain, 1986). Magmatic underplating is the deepest and most concealed component of the plumbing system in which mantle-derived magma accumulates at the base of the crust (e.g., Thybo and Artemieva, 2013) and is observed from seismic imaging and gravity studies, as well as being inferred from uplift history.

The interaction between ascending magma and the surrounding crustal rocks can lead to smearing of the geophysical signature of the underplated material, such that it is often difficult to identify the boundary that defines the precise depth of magmatic underplating (e.g., Thybo and Artemieva, 2013). The first geophysical investigations of underplating were done using gravity and

seismic surveys that suggested the presence of continuous layers of underplated material (e.g., Fowler et al., 1989). Higher resolution seismic surveys are able to produce improved images of magmatic underplating and consistently show the presence of high-velocity lower crust (HVLC) at the base of the crust, with varying geometries and thicknesses that range from a few kilometers to over 20 km. See Figure 4 and 5 for examples of underplate modelling that show the typical form and thickness of underplated material.

Current understanding of magmatic underplating and its relation to LIPs is limited. Few seismic surveys have been conducted in LIP environments to better constrain the location and geometry of the underplated material (Thybo and Artemieva, 2013). Furthermore, underplated material may or may not produce strong seismic reflectors depending on the mode of intrusion of the underplated material. For instance, sill-like intrusions will produce strong reflectors, whereas seismic imaging may not detect intrusions in the form of partially-solidified magma chambers (Thybo and Artemieva, 2013). However, it is generally accepted that buoyant magma reaching the base of the lithosphere can be channeled sideways or upwards, feeding a complex system of intrusions within the crust. Thus magmatic underplating plays an important role in the widespread distribution of magma throughout the crust.

Figure 4: Cross-section model of the 1115-1085 Ma Keweenaw LIP in the Lake Superior region of North America from seismic reflection data (GLIMPCE - Great Lake International Multidisciplinary Program on Crustal Evolution; Behrendt et al., 1990) and Bouguer gravity data (after Trehu et al., 1991 and Thomas and Teskey, 1994). The high-density lower crust is interpreted as mafic underplating at the base of the crust. From Miller and Nicholson (2013).

Figure 5: Magmatic underplating models from seismic data showing the general form and thickness of underplated materials from Thybo and Artemieva (2013). a) Modelling of the crust along a presently active rift zone in the southern Kenya Rift (Birt et al., 1997), showing a small high-velocity body near the Moho that is interpreted as mafic intrusions in the form of sills at the base of the crust. b) Mafic underplating modelled beneath the Donbas Basin in Ukraine (DOBREFraction Working Group, 2003). c) A particularly large underplate (Thybo and Schönharting, 1991) estimated to be 20 km thick is identified at the location of a large gravity high in the Norwegian-Danish Basin.

2.1.5 LIP Fragmentation

When attempting to understand the complete geological history of any individual LIP, uncertainties arise due to LIP fragmentation, which hinders the ability to recognize and correlate LIP-related fragments that end up as remnants on separate crustal blocks resulting from continental breakup (Ernst et al., 2005). Continental reconstruction is a powerful tool for restoring the fragmented components to their initial positions (e.g., Ernst and Srivastava, 2008; Ernst and Bleeker, 2010). Additional difficulties arise from erosional processes that can remove a major component of the LIP and expose the plumbing system, which appears as scattered ('fragmented') components of a LIP in the form of dykes, sills and layered intrusions (Ernst, 2007; Bryan and Ernst, 2008; Ernst, 2014a).

Tools for linking LIP fragments include geochemistry and LIP barcoding in which dated components or different crustal blocks are matched with the magmatic LIP record that can be used to correlate fragmented components of LIPs but, ultimately, these methods are limited (see Ernst, 2014a). Correlating LIP fragments can also be achieved by identifying buried and segmented components through more precise dating and geophysical modelling (e.g., Ernst et al., 2005). LIP fragmentation is very relevant to the present study since it is important to consider geophysical anomalies that are located near the plume centre, however this plume centre region may be fragmented and in some cases portions of the plume centre region can be located on several continents (e.g., the Central Atlantic Magmatic Province with fragments on Africa, Europe, and North and South America). Geophysical anomalies identified in the present study are therefore considered based on their nearness to the plume centre prior to fragmentation, and anomalies are investigated on all known fragments of the LIP.

2.2 Mineral Potential in Plume Centre Regions

Plume-related LIPs are excellent targets for mineral exploration because of their high melt volumes and metal reservoirs that are favorable for the formation of ore deposits (e.g., Ernst and Jowitt, 2013). Of particular interest to this study, there is a strong link between nickel (Ni), copper (Cu) and platinum-group element (PGE) deposits with mafic-ultramafic intrusions associated with LIPs (Table 3, Zientek, 2012). One of the most impressive examples is the Bushveld Complex that produces over 70% of the world's PGE reserves. There are also the Noril'sk-Talnakh intrusions in Siberia, linked with the Siberian Trap LIP, that together produce 30%, 8% and 35% of the world's nickel, copper and platinum group metal (PGM) reserves, respectively, making them the world's second largest producer of Ni-Cu-PGEs (Sluzhenikin, 2011). In fact, with the exception of Sudbury where a giant layered complex is interpreted to have formed as a result of a meteor impact and is considered sub-LIP scale, and a few smaller subduction-related deposits, most major Ni-Cu-PGE deposits can be directly linked with LIPs (e.g., Ernst and Jowitt, 2013).

Although LIPs make excellent targets for mineral exploration, perhaps the greatest difficulty is the vast areas that LIPs cover, which can extend to up to several millions of km² for an individual event. Narrowing the search radius is critical when conducting surveys. Geophysical surveys aid in surveying vast areas relatively quickly, however even so, they should be focused in areas of greatest mineral potential.

Studies of known mineral ore deposits suggest that the most prospective location for mineralization is within a few hundred kilometers of a plume centre (e.g., Ernst and Jowitt, 2013). Key examples include: the Noril'sk deposit (Figure 6a) located at about 300 km south of the plume

centre; the Muskox intrusion (Figure 6b) located about 400 km south of the Mackenzie plume; the Thompson Nickel Belt situated directly adjacent to the plume centre and the Raglan deposits (Figure 6c), which may have been ~500 km closer to the plume depending on when the opening of the Superior craton occurred (e.g., Ernst and Bell, 2010); and the Freetown layered complex associated with the 200 Ma Central Atlantic Magmatic Province (CAMP, Figure 6d), which is potentially a few hundred kilometers from the plume centre, but perhaps further depending on the reconstruction (e.g., Ernst and Jowitt, 2013). This paper focuses on layered intrusions within the proposed radius (several hundred kilometers from a plume centre), which are considered to be the most economically viable targets for exploration.

Table 3: Major Ni-Cu-PGE deposits linked with LIPs. LIP events are after Ernst, 2014a. Unless otherwise specified, the remaining references are Zientek (2012), and references therein.

Intrusion	LIP	Age (Ma)	Deposit Type
River Valley	Matachewan	2475 $\pm$ 2 -1	Contact-type deposits
Bushveld Complex	Bushveld	2054.4 $\pm$ 1.3	Reef-type PGE; Contact-type deposits
Thompson – Chukotat	Circum Superior	1880 $\pm$ 5; Hulbert et al., 2005	?
Muskox	Mackenzie	1269 $\pm$ 1; French et al., 2002	Reef-type PGE; Contact-type deposits; Gittings, 2001
Duluth Complex	Keweenawan	1095.94 $\pm$ 0.18	Contact-type deposits
Coldwell Complex	Keweenawan	1108 $\pm$ 1	Contact-type deposits
Jinchuan	Gubei	825	Contact-type deposits; Schulz, 2010
Noril'sk	Siberian Trap	250	Contact-type deposits; Schulz, 2010
Freetown	CAMP	200	Reef-type PGE; Bowles, 2000
Skaergaard	NAIP	55.59 $\pm$ 0.13	Reef-type PGE
Panton Sill	East Kimberly	1856 $\pm$ 2	Reef-type PGE
Penikat	Baltic LIP (BLIP)	2410 $\pm$ 64	Reef-type PGE
Mount General'skaya	Baltic LIP (BLIP)	2496 $\pm$ 10; 2446 $\pm$ 10	Contact-type deposit
Portimo Complex	Baltic LIP (BLIP)	2440 to 2435	Reef-type PGE; Contact-type deposits
Federova-Pana	Baltic LIP (BLIP)	2532 $\pm$ 6; 2496 $\pm$ 7	Reef-type PGE; Contact-type deposits
Great Dyke	Great Dyke of Zimbabwe	2575.4 $\pm$ 0.7	Reef-type PGE
Stillwater Complex	Stillwater	2704 $\pm$ 4	Reef-type PGE; Contact-type deposits
Munni Munni	West Pilbara	2935 $\pm$ 16	Reef-type PGE

Figure 6: The general distribution of major Ni-Cu-PGE deposits within LIPs. The most prospective area for mineralization is typically within a few hundred km of the inferred mantle plume centre (red star). A. 250 Ma Siberian Trap LIP with its Noril'sk-Talnakh deposits (the white star represents the plume centre inferred from a giant radiating dyke swarm; the solid red star is at the convergence of N-S and E-W rifting) B. 1270 Ma Mackenzie LIP and the Muskox intrusion. C. 1880 Ma Circum-Superior LIP and the Thompson Nickel belt and the Raglan deposits of the Cape Smith belt. D. 200 Ma CAMP LIP with the associated Freetown intrusion of Sierra Leone which may be as much as 1000 km away (depending on the tightness of the reconstruction). From Ernst and Jowitt (2013).

2.3 Economic Considerations

Metals associated with mafic-ultramafic intrusions are extremely valuable due to their unique properties. For instance, the Platinum-Group Metals (PGMs) iridium, osmium, palladium, platinum, rhodium and ruthenium are among the rarest elements in the Earth's crust. The most commercially important metals are platinum and palladium, but all are valued for their resistance to heat and catalytic properties. These are primarily used as catalytic converters in automobile exhaust systems to reduce harmful emissions. Other applications include glass production, jewelry, electronics and investment, among others (Wilburn and Bleiwas, 2004; Mudd, 2012; Loferski, 2015).

Similarly, nickel (Ni) is a good conductor of electricity and heat, as well as being resistant to corrosion at high temperatures. It is ductile, malleable, catalytic and has attractive colors, among other distinguishing qualities that make it highly valuable. About 65% of the Western world's supply of Ni is used to create Ni alloys, the most common of which is stainless steel. It is useful for plating to protect against heat and corrosion, and can also be found in rechargeable batteries, jewelry, coins and, due to its resistance to corrosion by sea water, and is invaluable in desalination plants.

Copper (Cu) shares many properties with nickel, but is the preferred electrical conductor in most electrical wiring. Additionally, it is a known antibacterial metal, meaning that it slows down the growth of germs such as E-Coli, making it invaluable in hospitals, as well as in the fabrication of monetary coins, doorknobs and plumbing systems. Similarly to Ni, it is easy to alloy, forming common Cu alloys including Bronze (Cu + Sn), Brass (Cu + Zn) and Cupro Nickel (Cu + Ni), making it particularly useful for pipework, tools and architecture (CCBDA, 1997-2015).

The unique properties of these metals, high cost and increasing global consumption make new mining targets extremely valuable and thus justify ongoing geophysical investigations of buried components of LIPs, particularly where economic potential is greatest.

3 Theory: Potential Field Methods in Exploration Geophysics

3.1.1 Introduction to Gravity Methods

On a regional or global scale, gravity measurements provide insight into the internal structure of the Earth, such as depth to Moho, while at local scales gravity can be used for mining and oil exploration purposes. Despite the dominance of seismic methods as primary exploration methods, gravity remains an important and commonly necessary tool in exploration. The gravity method is used frequently for mining purposes, and is regularly applied for the detection of shallow targets in the Earth's crust, such as dense ore bodies or cavities, for example (Nabighian et al., 2005).

The gravity method has advanced significantly over the past quarter century as technology, field operations, and data processing and interpretation are continuously improved (Nabighian et al., 2005). With progression from simple pendulums to land gravimeters and eventually to ship and airborne and borehole gravimeters, along with the development and improvement of Global Positioning Systems (GPS), surveys have been able to reach high enough accuracies to measure small variations in the Earth's gravitational field at precise locations on the Earth's surface that provide valuable insight into subsurface rock densities.

The following is a brief introduction to gravity theory and background information on data acquisition and processing techniques commonly applied in exploration.

3.1.2 Gravitational Acceleration

Newton's universal law of gravitation states that two bodies attract each other with a force F that is directly proportional to the product of their masses m_1 and m_2 , and inversely proportional to the square of the distance r between them

$$F = \frac{Gm_1m_2}{r^2} \hat{r}$$

where $G = 6.6732 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2$ is the universal gravitational constant and $\hat{r}$ is a unit vector along the line connecting m_1 and m_2 (Telford et al., 1990). If m_1 is the mass M_e of the Earth, m_2 is the mass m of an object at the Earth's surface and r is the radius R of the Earth, then for a spherical and uniformly dense Earth the force of an object resting on the Earth's surface is

$$F = \frac{GM_em}{R^2} \hat{r}.$$

According to Newton's second law of motion, the force acting on object is directly proportional to acceleration. On Earth, an object experiences the Earth's gravitational acceleration g . Thus

$$F = mg = \frac{GM_em}{R^2}$$

and the gravitational acceleration is

$$g = \frac{GM_e}{R^2}. \quad (1)$$

The average value of g at the Earth's surface is 9.8 m/s^2 ($1 \text{ m/s}^2 = 10^5 \text{ mgal}$),

3.1.3 Gravity Corrections

Deviations from a round, homogeneous Earth lead to measurable variations in the value of g across the Earth's surface. The gravitational field varies as a function of latitude, elevation, topography, Earth tides, and density variations in the subsurface (Telford et al., 1990). Therefore, prior to geological interpretation, the observed gravity data must be corrected to remove these unwanted effects. The main corrections are summarized here, however others exist such as correcting for instrument drift, for example.

After correction for all other variables that affect the measured value of g , then the resulting anomalies reflect density variations in the crust.

3.1.3.1 Latitude Correction

The value of g increases with latitude as a result of the elliptical shape and rotation of the Earth. An object at the North Pole experiences a pull towards the centre of the Earth due solely to the mass of the Earth. On the other hand, the same object at the equator is farther from the centre of mass of the Earth due to the equatorial bulge and additionally experiences an outward pull due to the rotation of the Earth. As a result, a gravity reading at the equator would read 5.2 gals less than at the pole. The latitude correction Δg_L is

$$\Delta g_L = 0.811 \sin(2\phi) \text{ mgal/km}$$

where ϕ is latitude (Telford et al., 1990).

3.1.3.2 Free-Air Correction

The free-air correction is a topographical correction. According to equation 1, g varies inversely with distance and therefore with station elevation. The free-air correction accounts for variations in measurement elevations, but does not account for excess (or a deficiency of) mass due to topographical effects (see below). The free-air correction Δg_{FA} is

$$\Delta g_{FA} = 0.3086h \text{ mgal}$$

where h is height in meters (Telford et al., 1990).

3.1.3.3 Bouguer Correction

The Bouguer correction Δg_B accounts for the excess (or deficiency of) mass between the station elevation and the datum plane that was not accounted for in the free-air correction:

$$\Delta g_B = 0.04192\rho h \text{ mgal}$$

where ρ is the density of the crustal rocks in g/cm^3 and h is height in meters (Telford et al., 1990). The data used in this study was corrected using a crustal density of $2.67 g/cm^3$.

3.1.3.4 Terrain Correction

Generally, the Bouguer and Free-air corrections are adequate when topography has minor effects on g , however in areas with considerable topographic variations, the terrain correction is applied and can account for large bodies of water such as seas or lakes where bathymetry data is available. The Terrain correction Δg_T is

$$\Delta g_T = 0.0419(\rho_w h_w + \rho_b h_b) \text{ mgal}$$

where $h_{w/b}$ and $\rho_{w/b}$ are the heights and densities of water (w) and bedrock (b), respectively.

3.1.3.5 Bouguer Anomaly

The corrections detailed above are applied in conjunction with conventional airborne gravity corrections including corrections for diurnal effects and instrumental drift. The resulting Bouguer anomaly Δg_B is the difference between the observed value of g (g_{obs}) and the theoretical (expected) value at a given station after corrections are applied:

$$\Delta g_B = \Delta g_L + \Delta g_{FA} - \Delta g_B + \Delta g_T$$

3.2 Magnetic Methods

3.2.1 Introduction to Magnetic Methods

The magnetic method is possibly the oldest geophysical exploration method (Nabighian et al., 2005). The earliest observations of magnets can be dated back to the 6th century B.C.E. by the Greek philosopher Thales, but the first investigation of the Earth's magnetic field dates back to the 16th century. Sir William Gilbert (1540 – 1603) demonstrated that the Earth can be approximated by a magnet oriented along the Earth's rotation axis (Telford et al., 1990). Due to the strong attraction of compass needles to iron, the first recorded successful survey was conducted by a Swedish mining company for iron-ore prospecting (Nabighian et al., 2005). Instruments used at this time consisted of a suspended needle that was free to move both vertically and horizontally, which provided an estimate of the ore body's location. Later improvements were made to the dipping-needle instrument in the 1860's and, although excellent at their time, these instruments were eventually replaced with inductor-based instruments that could measure the inclination as well as the magnitude of the field from voltage measurements (Heiland, 1940; Jakosky, 1950; Nabighian et al., 2005).

Magnetic instrumentation made the most notable improvement as a result of the Second World War, when airborne instrumentation such as the fluxgate magnetometer was developed and eventually used for exploration. Continual improvements to prospecting equipment have been achieved, including advances to data filtering, display and interpretation that follow directly from the availability of high-performance computers. Today, the magnetic method excels in a wide range of

applications including the use in constraining targets through inversion processes (e.g. Nabighian et al., 2005).

3.2.2 Magnetic Principles

Magnetic methods are similar to gravity methods in many respects. However, it can often be challenging to provide a quantitative investigation of magnetic data due in part to the wide range of magnetic susceptibilities for similar rock types, as well as directionality to the magnetic field that can drastically affect interpretation. Whereas gravity is an attractive force only, magnetic forces can be attractive *or* repulsive depending on whether the objects have opposite or like charges, respectively. Fortunately, a small number of magnetic minerals occur in high enough concentrations and are magnetic enough to make substantial contributions to the magnetic field, the most important of which is magnetite (Clark, 1997). Often, magnetic susceptibility is a function of the magnetite content in the rock and, to a lesser extent, to ilmenite and pyrrhotite.

The Earth can be approximated by a bar magnetic with lines of force that flow from the positive South Pole to the negative North Pole, similarly to a bar magnet. It is often convenient to consider a single magnetic pole m' by approximating a dipole as two single poles. This is best visualized by imagining two very long bar magnets placed side by side, with their positive ends adjacent to one another. Since each component of the dipole is so far away from the other, we essentially have an interaction between two single poles at each end of the magnets. The magnetic force F between two poles is given by Coulomb's Law:

$$F = \frac{1}{4\pi\mu} \frac{m_1 \cdot m_2}{r^2} \quad (2)$$

which states that two poles attract or repel each other with a force F that is directly proportional to the product of their magnetic strengths m_1 and m_2 , and is inversely proportional to the square of the distance r between them. The magnetic permeability μ is a property of the medium in which the

poles are situated. Equation 2 has important implications for magnetic surveying; mainly that the magnetic force falls off as the square of the distance between the source and the magnetometer (Reynolds, 2011).

The magnetic field measured during surveys is the secondary (or induced) field B which can be expressed as

$$B = \mu_0(H + M) \text{ SI Units}$$

where $\mu_0 = 4\pi \times 10^{-7} \text{H/m}$ is the permeability of free space, H is the magnetic field of the Earth and the magnetization M is the vector sum of induced M_i and remanent M_r magnetization components

$$M = M_i + M_r.$$

Induced magnetization M_i is proportional to the magnetic susceptibility χ , which is the degree of magnetization a material undergoes in response to an external magnetic field:

$$M_i = \chi H$$

The total magnetic field of the Earth is often expressed in nT. In SI units, the Earth's magnetic field is on the order of 10^5 nT.

3.2.3 Magnetic Corrections

The ultimate goal of the magnetic method is to detect local variations in rock susceptibilities. Similarly as is done with gravity data, corrections are applied to the magnetic data. These include similar corrections such as correcting for diurnal variations in the field, which in the case of magnetism are due primarily to solar effects. Additional modifications include subtracting the International Geomagnetic Reference Field (IGRF; Maus and MacMillan, 2005) from the total field, which is often advantageous when the goal is to detect small variations in the Earth's magnetic field for exploration purposes, as well as reduction to the pole (RTP).

RTP is applied to correct for latitude effects and is done by applying a filter to the data that produce the anomaly map that would have resulted had the survey been conducted at the magnetic pole. This method was first developed by Baranov (1957) and Baranov and Naudy (1964), and assumes that the entire measured field is due to magnetic induction. This means that RTP is complicated when remanent magnetization is present within the rocks. In our case, modelling in Oasis Montaj allows for the direct modelling of magnetic data not reduced to the pole, however this technique (reduction to the pole) is still applied in the current study to compare gravity and magnetic anomaly maps with the purpose of determining whether the gravity and magnetic anomalies are coincident and caused by the same source.

3.3 Potential Field Methods

A starting model is often invaluable in the modelling process and can provide insight towards interpreting the Bouguer and magnetic anomalies. The first order approximation of the causative body in a starting model will often be a simple geometric shape. In the case of modelling using gravity data, estimates of the body's density, volume, depth to centre of mass and limiting depth are assumed and incorporated into the model, and similar applications exist for magnetic data. The synthetic gravity and magnetic data are compared to the observed data and the model is adjusted to reduce the error between the two. The following is a brief introduction to potential field methods using gravity as an example; however similar rules can be applied for magnetic potential field data.

A common method for gravity interpretation is an application of the Smith rules (Smith, 1959) which are based on a gradient to amplitude ratio. Limiting depth estimates (the depth to the upper surface of the causative body) are particularly useful because they can be applied to any geometrical shape. The limiting depth equation is

$$d \leq 0.86 |\Delta g_{\max}| / |\Delta g'_{\max}|,$$

where d is the limiting depth, $\Delta g_{\max}$ is the maximum gravity anomaly amplitude and $\Delta g'_{\max}$ is the maximum gradient across the anomaly (Figure 7).

In cases where the geometry of the body is pre-assumed, the depth to centre of mass z can be estimated from half-width measurements. The limiting depth and the depth to the centre of mass of several simple bodies are provided in Table 4 (refer to Figure 7). The causative body will typically have a more complicated geometrical shape than those provided in Table 4, so the model will commonly involve some shape that lies between the end members listed in Table 5.

Figure 7: Limiting depth estimates from gradient to amplitude ratios, where $\Delta g_{\max}$ is the maximum gravity anomaly amplitude and $\Delta g_{\max}'$ is the maximum gradient across the anomaly. The half-width ($X_{1/2}$) is measured at half the maximum amplitude ($0.5 \cdot \Delta g_{\max}$). z represents the depth to centre of mass and d represents the limiting depth of the body. Modified from Smith (1959).

Table 4: Depth estimates from gravity half width $x_{1/2}$ measurements for simple shapes.

	Depth to centre of mass (z)	Limiting depth (d)	Comments
Sphere	$z = 1.305 x_{1/2}$	$d = z - r$	radius r
Horizontal cylinder	$z = x_{1/2}$	$d = z - r$	radius r
Vertical cylinder	$z = 1.732 x_{1/2}$	$d = z - l$	length l
Steeply dipping sheet	$z = 0.7x_{1/2}$		

3.4 Rock Properties

Density is a good indicator of rock type and is particularly useful at differentiating high density mafic and ultramafic rock from low density sedimentary and country rock (see Table 5). Magnetic susceptibility, on the other hand, varies over orders of magnitude for each rock type, making it a much less accurate indicator of rock type (see Table 6). For instance, mafic-ultramafic rocks tend to be magnetic, but the level of magnetism varies and depends largely on the magnetic content in the rock. The degree of magnetization can also vary due to weathering or alteration. For instance, ultramafic rocks at the base of layered intrusions are usually serpentinized, often containing chromite and abundant secondary magnetite (e.g., Clark et al., 1992), such as is observed within the tholeiitic Skaergaard, Bushveld and Stillwater intrusions, which produces a strong magnetic signal as magnetic susceptibility values increase with degree of serpentinization (Lowe et al., 2003). Also, being a hydration process, serpentinization results in a volume increase and a density decrease.

Additional complications in characterizing magnetic rocks using magnetic data are caused by the presence of highly magnetic country rock and overlying sediments (King, 2007). In general, density contrasts are more easily interpreted from gravity data and is therefore often more reliable at differentiating rock type; however magnetic data can be useful for identifying large anomalies (e.g. the HALIP magnetic anomaly, section 6.5), as well as for constraining models. The approach taken here is to identify potential targets for investigation using both gravity and magnetic anomalies, and to do joint modelling of gravity and magnetic data.

Table 5: Rock Densities. Compiled from Telford et al. (1990).

Lithology	Range (g/cm ³)	Average (g/cm ³)
Mafic Igneous	2.09 – 3.17	2.79
Felsic Igneous	2.30 – 3.11	2.61
Ultramafic rocks (Peridotite)	2.78 - 3.37	3.15
Metamorphic	2.40 – 3.10	2.74
Sandstone	1.61 – 2.76	2.32
Shale	1.77 – 2.45	2.42

Table 6: Rock Susceptibility Values. Magnetite and pyrrhotite content will have a major effect on the magnetic susceptibilities of the rocks and are added at the end of the table for reference. Compiled from Telford et al. (1990).

Lithology	Range (cgs)	Average (cgs)	Average (SI)
Mafic Igneous	$4 \times 10^{-5} - 0.01$	0.0026	0.033
Felsic Igneous	$3 \times 10^{-6} - 0.007$	6.5×10^{-4}	0.0081
Ultramafic rocks (Peridotite)	0.007 – 0.016	0.012	0.15
Ultramafic rocks (Fully Serp.)	0.001 – 0.1*	0.05*	0.63*
Metamorphic	0 – 0.006	3×10^{-4}	0.004
Sandstone	0 – 0.002	3×10^{-5}	0.0004
Shale	$5 \times 10^{-6} - 0.0015$	5×10^{-5}	0.0006
Sulphides/Oxides			
Magnetite	0.095 – 1.53	0.48	6.03
Pyrrhotite	0 – 0.48	-	-

*Clark et al., 1992

$$1(\text{cgs}) = 4\pi(\text{SI})$$

4 Project Data Sets

4.1 EGM2008

The Earth Gravitational model EGM2008 (Pavlis et al., 2012) is a spherical harmonic model of the Earth's gravitational potential field, developed by a least squares combination of a GRACE-derived satellite-only model (ITG-GRACE03S; Mayer-Gürr, 2007) with a global 5 arc-minute resolution grid of free-air gravity anomalies provided by the NGA (National Geospatial-Intelligence Agency). The grid was merged from terrestrial, altimetry-derived and airborne gravity data. In this way, long-wavelength information from Grace satellite data was merged with short wavelength data from the 5 arc-minute grid to produce a high-resolution global gravity model.

The availability of high-resolution data contributing to the 5 arc-minute grid varies depending on location (Figure 8a). As a result, the accuracy of the model also varies depending on location. For instance, North America and Australia have the highest accuracy with the majority of values lying within ± 1.5 mgal, while the southern pole is modelled solely by GRACE satellite data (Figure 8b) and has the lowest accuracy (Figure 9). This thesis focuses on LIPs distributed over four regions: Arctic Canada, eastern South America, western India, and Africa. Data is available for all regions of interest to this study with most values having an accuracy of at least ± 3 mgal.

The global coverage offered by EGM2008 is ideal for a global geophysical investigation of LIPs. Additionally, due to the nature of the thesis, resolution and accuracy offered by the EGM2008 is high enough to detect regional-scale anomalies that are the focus of this study.

Figure 8: a) Global map of EGM2008 data availability. Areas in green denote unrestricted data that was used in calculating the 5' x 5' grid. Regions in grey denote proprietary data that were made available at the resolution required to estimate the 5' x 5' grids in agreement with the owners. Regions in red denote areas where gravity data was either unavailable or too sparse to support the estimation of the 5' x 5' grid. b) Data source identification. From Pavlis et al. (2012).

Figure 9: Global map of $5' \times 5'$ Δg data standard deviations. From Pavlis et al. (2008).

4.2 EMAG2

EMAG2 (Figure 10) is a global 2-arc minute Earth Magnetic Anomaly Grid modelled at 4 km above the geoid compiled from CHAMP satellite, ship and airborne measurementsⁱ. The data set was compiled by merging existing grids using least squares collocation into a common global grid, by processing ship and airborne measurements, merging track line data and substituting spherical harmonic degrees ≤ 120 (≥ 330 km wavelength components) with the CHAMP satellite magnetic anomaly model MF6 (Maus et al. 2008).

For the current study, the majority of study areas have complete coverage by the EMAG2. In the rare case where data coverage was not complete across the study area, magnetic data is interpolated in this study using thin-plate spline techniques.

Figure 10: Global 2 arc minute Earth Magnetic Anomaly Grid (EMAG2)

4.3 CRUST1.0

CRUST1.0 (Laske et al., 2013) is a 1×1 degree resolution model of the Earth's crust with estimates of the depth to Moho, as well as thickness and density estimates of crustal layers (i.e. sediments, and upper, lower and middle crust). The Moho depths are based on crustal thickness data from active source seismic studies and receiver function studies. In areas where seismic constraints are lacking, crustal thicknesses were estimated using gravity constraints.

These layers were incorporated into the modelling to provide estimates of the depths to Moho in the study areas, as well as upper, middle and lower crust thicknesses and densities. Estimates of sediments were similarly incorporated into the model but were permitted to vary slightly during model optimization.

5 Modelling Software and Methodology

Modelling is done in Geosoft Oasis Montaj profile modelling software GM-SYS. Data are in the form of pre-processed grids that cover a global extent (sections 4.1 and 4.2) and are incorporated into a profile model once a geophysical anomaly is selected for further study (Section 6), (Figure 11; step 1). Because the amplitude of a given anomaly may appear larger or smaller than its true value due to the background contribution, all anomalies are quoted relative to background values. In this way, anomalies located at different locations on the Earth's surface can be compared.

Since modelling is done at regional-scales, which is most applicable towards large intrusions (several 10's of kilometers in length), long wavelength components were not removed from the observed data for modelling, which reduced any bias that would have been introduced by such a filtering process. However, wavelength filtering was often applied to provide insight into the shape of the bodies at various depth levels to aid in constructing a starting model. For example, a short wavelength map may show a small body and progressively longer wavelength maps (corresponding to deeper bodies) may show an increase in size of a body with depth. This method was often applied alongside the potential field methods described in section 3.3 to provide a first order approximation of the body of interest.

GM-SYS is a tool used to calculate the geophysical response of a cross-section model using forward modelling and inversion. Forward modelling involves creating a hypothetical model that is a best guess of the subsurface geology and calculating the response of the model. The observed data and the calculated response can be compared, and the model adjusted to reduce the error between the two. Forward modelling produces a unique solution, meaning that a single response will be calculated for the given model. Inversion, on the other hand, involves the opposite procedure where

a model is calculated from the geophysical data that represents the best fit to the observed data. Inversion is by nature a non-unique process, meaning that an infinite number of solutions can produce the same geophysical response. Furthermore, a given model may fit the observed data very well, but may not make sense geologically. In the present case, the geophysical data being modelled are gravity and magnetic data.

A given cross section is carefully chosen so that a model across the section will best represent the causative body. There is no one method for selecting profile lines, so each case is considered separately. Given that the majority of anomalies are identified from gravity data, the profile lines are often selected based on the dimensions of the gravity anomaly, however the opposite is true when the body is identified from magnetic data (Figure 11, step 2). Profile lines that intersect the identifying anomaly (gravity or magnetic) along one or both of its axes are selected, while the secondary data set (gravity or magnetic) is still considered. When possible, this profile line is selected along the axis that is oriented in the same direction as the line that connects the anomaly to the proposed plume centre. When a second profile model can provide additional insight into the subsurface, the second line is selected to be perpendicular to the first.

A starting model is created in GM-SYS using layers that represent crustal layers reflective of an increase in density with depth, and blocks that represent anomalous geological units (for example, an intrusive body), each of which is assigned physical property values. The crustal layers are created from a 1-degree model of the Earth's crust (CRUST1.0), which estimates the depths to the upper, middle and lower crust, depth to Moho and sediment thickness, as well as densities for each layer (Figure 11, steps 3,4 and 5). Each layer is provided in grid format with two components: layer thickness and layer density. In order to be able to use this data in Geosoft, crustal layers grids are

converted into depth grids relative to the topographic or bathymetric grids (Becker et al., 2009). Density values provided by CRUST1.0 for each layer are averaged along the profile line and assigned to the entire layer in order to simplify modelling. Magnetic susceptibility values are not provided by CRUST1.0 and instead were estimated from typical textbook values normally associated with the rock types found within the crust (e.g. Telford et al., 1990)

Gravity data is added directly to the GM-SYS profile modelling window, however additional parameters must be included for magnetic data. GM-SYS provides an alternative to reduction to pole, where the Earth's magnetic field parameters at the time and location of the survey, as well as survey parameters such as survey altitude, are defined in the modelling window (Figure 11, step 6). In this way, the response of the model can be directly compared with the observed magnetic data without the need to reduce the data to the pole for the purposes of modelling. Due to the gridded nature of the data, the original station locations are not known. As a result, the gravity and magnetic grids are sampled at roughly 4 km intervals, which represent theoretical station locations. Due to the regional scale anomalies that are modelling (often between 50 and 100 km across), a 4 km interval provides sufficient detail of the gravity and magnetic variations across the profile lines.

The intrusive body is added to the model by using potential field methods for gravity and magnetic data (Figure 11, step 7) that allow for an initial guess of the geometry and depth of the intrusion. This body is assigned a density and magnetic susceptibility that is permitted to vary within reasonable values throughout the modelling process.

Physical properties values can vary considerably within the same rock unit. Modelling is simplified by assigning average rock property values to each unit (Table 5 and 7). The models are optimized in two ways (Figure 11, step 8): 1) the model is adjusted manually to reduce the error

between the observed and calculated data while including geological considerations into the model, and 2) the model is adjusted using joint inversion of gravity and magnetic data using inversion algorithms that require geological knowledge for effective modelling. Combining the two methods allows the model to converge to a solution reasonably fast while ensuring the continued consideration of geological “reasonableness”. During the optimization process, the upper, middle and lower crust layers are held constant, while the properties of the causative bodies and sedimentary layers are allowed to vary. Typically, the intrusions being modelled tend to be elongated and as a result, the intrusive body is shallower than the initial guess introduced into the starting model.

The inversion process may be configured to vary one or several parameters simultaneously. The practice used for this study is to hold density and magnetic susceptibility relatively fixed (meaning they are held within realistic rock property limits), while the horizontal and vertical positions of layers and bodies within the model are allowed to vary within limit (typical limits used are 300 meters per iteration in both the x and z directions). Additional constraints include the relative weighting of gravity and magnetic data (Grav:Mag) that is allowed to vary between 1 and 0 and which was typically varied between 0.5 and 1 for this study, enforcing in some cases a stronger priority on gravity data. Unknown remanent magnetization in the rocks can lead to errors when modelling magnetic data. In some cases the remanence direction was known from studies on nearby units exposed in outcrop; if so then the remanence was incorporated into the model. When remanent magnetization is suspected, but values are not provided in the literature, modelling is focused primarily on reproducing the gravity data while using the magnetic data as a constraint. In these cases, estimates of remanent magnetization are attained through modelling in this study.

A model is accepted when it is considered to be geologically realistic and when the fit between the observed data and the calculated response of the model is below a certain threshold. The goodness of fit is determined by the Root Mean Square (RMS) error between the observed and calculated data. A constant value (or DC-Shift) is added to the gravity and magnetic data to force the calculated and observed values to match or at least be in the same absolute range. This is necessary because the gravity or magnetic response of the model is an absolute calculation, whereas the observed data are corrected for the reference geoid. The RMS is measured between the two data sets *after* the DC-shift is applied and is reduced through manual adjustments of the model. An RMS value of 0 would indicate a perfect fit between observed and calculated data; however, this is unlikely due to unknown variables in the model, such as complex geology that is not expected or inferred from geological maps of geophysical data, that will produce errors between the response of the model and observed data.

Acceptable error on a model is highly subjective and varies as a function of the amount of geological and geophysical control on the subsurface and is likely to vary depending on the interpreter and the aim of the study (e.g., Hinze et al., 2013). In this study, regional-scale anomalies produced by large intrusions are investigated. Therefore, we are more concerned with reproducing long-wavelength features and less with reproduced short-wavelength (< 1 km) components of the gravity and magnetic data, although attempts are made to best reproduce all data when possible.

In this study, the models tend to become insensitive to further inversion iterations once they reach an RMS value of about 5 mgal for gravity data, which, for this reason, is our target error for gravity. However, the error estimates for magnetic data tends to be much larger (up to about 60 nT). Due to the number of sources of error in gravity and magnetic modelling, the RMS value is not the

only metric used to determine the success of a model. For example, the RMS value will increase drastically when short-wavelength features exist in the data (i.e. the response of near-surface bodies). Since this thesis focuses on large bodies that typically produce large-wavelength signals, near-surface bodies are sometimes not modelled, especially when these smaller units are not directly above the intrusion of interest. In many cases, a visual inspection between the observed and modelled response is used to assess the goodness of fit for the anomaly being modelled. Additional constraining data leading to an increase in geological control would improve the resolution of near-surface features; however these data are often not available in the regions being studied.

Both 2-D and 2.5-D modelling are supported in GM-SYS. 2-D modelling assumes a 2-dimensional Earth, however 2.5-D modelling assumes a 3-dimensional Earth and allows the interpreter to vary the extent of the layers and prisms created in the model in the third dimension. 2.5-D modelling was applied during the course of this study that allowed for the manipulation of blocks in 3 dimensions.

Figure 11: Generalized methodology steps. Magnetic anomaly map (left) and Bouguer gravity anomaly map (right) showing one of the anomalies investigated in this study situated on Ellesmere Island, Nunavut. In general the anomalies are identified using gravity and/or magnetic data and are selected based on criteria outlined in section 6.1 (**Step 1**). The cross section(s) is selected across the anomaly for modelling purposes (**Step 2**). Star indicates the location of the plume centre.

Step 3, 4 and 5: Crustal layers are added to the model from CRUST1.0. Layers are provided as thickness grids and are converted into depth grids relative to topography before being incorporated into the model. Density grids are averaged along the profile line and the average density value is assigned to each layer to simplify modelling. Magnetic parameters (not provided in CRUST1.0) are estimated from typical magnetic properties of the crust.

Step 6: Gravity and magnetic field data are added to the model. The Earth's magnetic field and magnetic remanence parameters are added to the modelling window.

Step 7: The causative body (or bodies) is generated using first order approximation techniques (section 3.3) and the density and magnetic susceptibility estimates are defined.

Step 8: The model is optimized iteratively using a combination of joint inversion techniques and manual optimization until an acceptable model is achieved. Usually the final step is manual edits for final 'touch ups' to the model.

6 Results

6.1 Reconnaissance Survey of Plume Centre Regions

The vast extent of LIPs and the large number of geophysical anomalies occurring within LIP boundaries (both related and unrelated to the LIP), considerably increases the complexity of a survey that aims to identify LIP-related intrusions using a geophysical approach. An attempt is made to minimize the search area while increasing the likelihood of detecting intrusions both related to a LIP and which are important from a Ni-Cu-PGE economic perspective. Herein, a methodology is developed for identifying major layered intrusions linked with LIPs using two geophysical techniques, gravity and magnetics. Each is sensitive to different physical rock properties and provide a complementary understanding of the characteristics of buried intrusions.

In the present study, we begin to characterize the plumbing systems in plume centre regions and this is done by characterizing the depth and spatial distribution of such intrusions. For instance, layered intrusions may build at the base of the crust as a magmatic underplate, and then also build at higher levels in the crust, both as deep or shallow chambers. Also, depending on the depth of erosion in the plume centre region, some layered intrusions may be exposed at the surface. There may also be compositional differences with depth. On the basis of density it might be predicted that ultramafic layered intrusions will be preferentially emplaced at deeper levels in the crust with more mafic (gabbroic) compositions at shallower levels in the crust.

Additionally, with the goal of characterizing the spatial distribution of layered intrusions in plume centre regions, LIPs are classified based on the types of intrusion distributions observed in their plume centre regions. This has important implications for understanding how the intrusions

were emplaced and can be used to correlate LIPs based on the different ways in which magma is distributed throughout their plumbing systems. The distribution of intrusions linked to a LIP can also have implications for identifying plume centre locations.

A survey of 18 LIPs distributed globally (Figure 12) is conducted in order to identify geophysical anomalies that are good candidates for layered intrusions linked with a LIP. These LIPs were selected from the global LIPs catalogue that comprises a total of 211 LIPs (Table 1.2 in Ernst, 2014a). The selected candidates were those for which a reasonably well-defined plume centre has been identified. Often, the plume centres are identified at the focus of a giant radiating dyke swarm or triple junction system, but other methods include locating a plume centre at a centre of domal uplift, for example, which leads debate over the exact position of the plume centre. However, in general, these proposed plume centres are very near one another and define a relatively well-defined centre.

In each case, geophysical data were examined over an area that lies within a radius of about 500 km from the plume centre, which is generally referred to as the plume centre region. Based on experience with the Mackenzie LIP (e.g. Baragar et al. 1996), this area encompasses the extent of major intrusions associated with the plume centre. Geophysical anomalies were selected based on five key criteria:

- i. Proximity to the plume centre. Anomalies near the plume centre are selected for study as they are the most easily and reliably correlated with a given LIP.
- ii. Spatial distribution in the plume centre region. Simple geometrical patterns of intrusions near a plume centre can imply how the intrusions were emplaced and link them with a LIP. For example, intrusions can be linked with a LIP by an obvious relation with plume-induced

ripping, which would occur as circular geophysical anomalies linearly aligned along a rift structure.

- iii. Large sizes. Large intrusions imply large-scale magmatism as their source, and are consequently more likely to be correlated with LIP-scale magmatism. Therefore, large geophysical anomalies (several 10's of kilometers) are targeted. Large intrusions also represent a major component of the LIP plumbing system and are therefore of primary interest in a study that aims to characterize LIP plumbing systems.
- iv. High anomaly amplitudes. Prominent gravity and magnetic anomalies imply high-density and high-magnetic susceptibility rocks, both of which commonly occur in mafic-ultramafic intrusions. Typically, gravity anomalies that are at least + 30 mgal above background values, and magnetic anomalies that are several hundred nT above or below background values are considered for this study.
- v. Circular to oval anomalies. Geophysical anomalies that are subcircular are more likely to be caused by layered intrusions, which themselves are often emplaced with some degree of radial symmetry, as opposed to linear-belt-type anomalies that are more likely to be related to rift zones or basement ribbon terranes.

In all cases, local geology and tectonic history are also considered to exclude from further consideration those anomalies not likely due to mafic-ultramafic intrusions. This includes LIP fragmentation (section 2.1.5), which means that anomalies are considered based on their proximity to the plume centre at the time of magmatism, and not necessarily due to their current position near a plume centre. The best candidates are where a high-amplitude, subcircular geophysical anomaly with a diameter of at least several 10's of kilometers is situated within a few hundred kilometers of a plume centre and is located in a region where the background gravity and magnetic signals are smooth and quiet.

6.1.1 Candidates

In the present study, most anomalies are identified from gravity data as these anomalies tend to be better defined than magnetic anomalies. This is due largely to the high density contrast between mafic-ultramafic rocks and country rock, although the gravity anomalies commonly coincide with magnetic anomalies.

The LIPs that are investigated (Figure 12) and the geophysical anomalies that are considered as good candidates for layered intrusions are summarized in Table 7, and are briefly summarized in the following paragraphs. More detail is provided for the LIPs in which geophysical anomalies were selected for modelling in sections 6.2 to 6.5. It is important to note that while a large number of the anomalies are identified for the first time in this study, some of the anomalies coincide with well-known intrusions (identified through geophysical modelling in previous studies) and still others are known anomalies but have never been investigated quantitatively using geophysical modelling. These are highlighted in Table 7 with appropriate references as they have important implications in our study of the spatial distribution of layered intrusions.

The 66 Ma Deccan Traps in India (Figure 13 and 15, Table 7) hosts numerous mafic-ultramafic intrusions that are identified from gravity and are almost all located along major rift zones (Figure 13, inset). The Bouguer anomaly map of western India delineates 7 sub-circular gravity highs within a few hundred km of the plume centre (star). Near Bombay (Mumbai) and Surat, the anomalies D5, D6 and D7 are located along the West coast rift. Modelling of these anomalies (D5, D6 and D7) (Bhattacharji et al., 2004) infers the presence of a continuous mafic-ultramafic-type intrusion at 6 km depths. The same study also identifies eight layered intrusions along the Narmada-Tapti rift system. Anomalies D4A and D4B are reported as mafic-ultramafic volcanic plugs coeval with Deccan

magmatism (Chandrasekhar et al., 2002). Anomalies D1, D2 and D3 are located along the Cambay rift in Eastern Saurashtra and have often been alluded to (e.g., Mishra et al., 2001, Chandrasekhar et al., 2002), but these have never been modelled. These geophysical anomalies (D1, D2 and D3) are selected for modelling in the present study and are further detailed in section 6.4.

The 130 to 80 Ma High Arctic LIP (HALIP; Figure 14) has a plume centre ~ 200 km off the western coast of Ellesmere Island, Arctic Canada. A prominent circular + 850 nT magnetic anomaly is situated on the western edge of Ellesmere Island at about 100 km from the plume centre (

Figure 14, Table 7). It is the only anomaly of its kind in the plume centre region, and was provisionally interpreted to be the expression of a mafic-ultramafic layered intrusion linked with

HALIP magmatism based on its position near the plume centre and the presence of HALIP-aged plutonic and volcanic rocks observed in the area (Jowitt et al., 2014), but was not investigated further. Modelling is conducted across the unit in the present study to provide further insight into the source of the anomaly and the results are discussed in section 6.3.

The 0.13 Ga Paraná-Etendeka has LIP fragments on the South American and African continents (Figure 15). On West Africa, there are two gravity anomalies that are situated within a few hundred kilometers of the plume centre (Figure 15, Table 7). The gravity anomaly PE1 is a subcircular, + 60 mgal gravity anomaly with a diameter of 450 km that is located at 365 km from the plume centre. To the south, the gravity anomaly PE2 is less defined, but is a second potential subcircular gravity anomaly at 600 km from the plume centre. This anomaly PE2 is more than 100 km across and has an amplitude of + 30 mgal. The nature of these anomalies is not certain, particularly due to the fact that they are not as well defined as other anomalies observed in the present study and because it is unclear if they are related to the Paraná-Etendeka LIP. This is particularly true for the second anomaly PE2 that is beyond the plume centre region. For this reason, no further modelling is done at this site in the present study.

In northern Canada, at least eight + 49 to + 132 mgal gravity anomalies are located in the vicinity of the 1270 Ma Mackenzie and 720 Ma Franklin LIP plume centres on Victoria Island and northern Banks Island, respectively (Figure 16, Table 7). M1 to M5 are gravity anomalies that have been previously recognized (e.g., LeCheminant and Heaman, 1989; Baragar et al., 1996), but modelling was not done to characterize these intrusions. They are interpreted as being linked with Mackenzie magmatism due their circumscribing nature around the Mackenzie plume centre, in addition to a link with the Muskox intrusions (Hornal, 1968; Gittings, 1990) which is a component

of the Mackenzie LIP. Herein, an additional gravity anomaly M6 is identified and considered as a continuation of the Mackenzie intrusions circumscribing the plume centre. Less understood are the anomalies A1 and DB, the latter of which is the + 132 mgal Darnley Bay anomaly that coincides with a + 1350 nT magnetic anomaly. Although the Darnley Bay anomaly has been explored for Ni-Cu-PGE's, the main body remains to be intercepted via drillcore and the origin of the intrusion remains unclear. Either of these intrusions (DB and A1) can be related to the either of the Franklin or Mackenzie LIPs. Anomalies M1 – M5 are modelled in the present study and detailed in section 6.2 (M6 was considered for modelling, but rejected based on complicated background geology that made the model less reliable).

The c. 1380 Kunene-Kibaran LIP in East Africa (Figures 12 and 17) hosts a number of granitic and mafic-ultramafic intrusions above a proposed plume at the centre of a giant arcuate dyke swarm (LVDS) with an outer radius of 500 km and 180° arc (Figure 17, inset), (Tack et al., 2008; Mäkitie et al., 2014). Three + 50 to + 120 gravity anomalies (LV1, LV2 and LV3) are situated along the outer periphery of the LVDS, ranging in size from 80 km to more than 200 km across, and are interpreted to be a component of Kunene-Kibaran magmatism. LV1, LV2 and LV3 may represent a partial component of a circumscribing pattern of anomalies (which is concave to the west) similar to the Mackenzie circumscribing intrusions. The western component may be missing due to the presence of the western branch of the East African Rift System, or may not be detected due to a lack of surveys to the west (Mäkitie et al., 2014). Modelling is conducted across LV1 and LV2 to better characterize the intrusions (section 6.3). LV3 was considered for modelling but rejected based on the fact that it is aligned with the western branch of the East African Rift System that severely complicates modelling at this location.

The 1890 Ma Bastar-Cuddapah LIP (Figures 12 and 18) is distributed over eastern and central India. In East India, a prominent + 60 mgal gravity anomaly is located at 420 km from the plume centre (Table 9). The anomaly is oval in shape with dimensions of 80 × 50 km, and has been interpreted by Grant (1983) to be a 4 km-thick sill-like layered intrusion sitting at a depth of 7 km, and considered to be a funnel-shaped intrusion in the upper crust by Chatterjee and Bhattacharji (2001), with densities ranging between 3.0 to 3.2 g/cm³ which correspond to olivine-gabbro in the funnel and feldspathic peridotite in the feeder zone. The Cuddapah intrusion is an example of a regional-scale layered intrusion linked with a LIP (Radhakrishna et al., 2007; Ernst and Srivastava, 2008), emplaced near the plume centre that can be detected from gravity based on its amplitude and size, as well as its proximity to the plume centre. Further modelling is not done at C1, however the intrusion is considered in our investigation of the spatial distribution of intrusions in plume centre regions.

Four of these LIPs were selected for further study, based on the number of good candidates identified within their plume centres, in which eleven anomalies from these four plume centre regions were modelled to provide insight into their source depth, composition and lateral extent, and to properly represent a major component of the LIP plumbing system. The modelling results are detailed in sections 6.2 to 6.5.

Figure 12: Global distribution of LIPs investigated. Colored LIPs, corresponding to HALIP (green), Mackenzie (purple), Kunene-Kibaran (blue) and Deccan (red), are those that were modelled in detail. Modified from Ernst (2014a).

Table 7: Geophysical investigation of 18 plume centre regions listed in chronological order. A hash symbol indicates that anomalies were investigated, but none were considered as good candidates for layered intrusions associated with a LIP based on criteria detailed in the text. In the case where a LIP was fragmented, the plume centre is quoted with respect to each landmass. Ages are from Ernst 2014a. Anomaly amplitudes are quoted with respect to the background signal in the region. Plume centre locations at the time of emplacement after: 1 - Ernst and Buchan 2001a; Ernst 2014a; 2 – White and McKenzie, 1989; 3 – Ernst and Buchan 2002; 4 – Ernst and Buchan 1997; 5 – Ernst and Srivastava 2008; 6 – Buchan and Ernst 2006; 7 - Mäkitie et al. 2014.

Large Igneous Province /Location	Plume Arrival (Ga)	Plume Centre Location (Long, Lat)/ Plume name	Evidence for intrusions	Distance from Plume Centre	Amplitude	Shape and Size	Comments and link to Figures
Columbia River (North America)	0.02	(118°W,42°N) ¹ W. NA Yellowstone	-	-	-	-	-
Afro-Arabian (Afar) (East Africa, Arabian Peninsula)	0.03	(41°E,11°N) ² Afr. Afar	-	-	-	-	-
NAIP (Europe, Greenland)	0.06	(15°W,65°N) ² GL Iceland	-	-	-	-	-
Deccan (India)	0.06	(72.5°E,21.5°S) ¹ Ind. Réunion	Gravity	221 km	+ 70 mgal	Subcircular <i>d</i> = 45 km	D1; Figure 13
				223 km	+ 50 mgal	Subcircular <i>d</i> = 35 km	D2; Figure 13
				240 km	+ 67 mgal	Subcircular <i>d</i> = 40 km	D3; Figure 13
				414 km	+ 80 mgal	Subcircular <i>d</i> = 80 km	D4A; Figure 13 (D4B denotes a strong magnetic anomaly)
				233 km	+ 70 mgal	Elongated 140 × 60 km	D5 (Bombay); Figure 13, interpreted as layered intrusion; see Bhattacharji et al. (2004)
				133 km	+ 30 mgal	Subcircular <i>d</i> = 35 km	D6 (Surat); Figure 13
				90 km	+ 30 mgal	Subcircular <i>d</i> = 35 km	D7 (Surat); Figure 13

Large Igneous Province /Location	Plume Arrival (Ga)	Plume Centre Location (Long, Lat)/ Plume name	Evidence for intrusions	Distance from Plume Centre	Amplitude	Shape and Size	Comments and link to Figures
Madagascar (Africa)	0.09	(47°E,24°S) ¹ MD	-	-	-	-	-
HALIP (Circum Arctic)	0.13 – 0.09	(92°W,83°N) ⁵ Can.	Magnetics	80 km	+850 nT	Subcircular <i>d</i> = 40 km	Figure 14
Paraná-Etendeka (S. America and SW Africa)	0.13	(46°W,27°N) ³ E. SA	-	-	-	-	-
		(10°E,13°S) ³ W. Afr.	Gravity	365 km	+60 mgal	Subcircular <i>d</i> = 80 km	PE1, Figure 15
			Gravity	600 km	+30 mgal	Subcircular <i>d</i> = 120 km	PE2, Figure 15
Karoo- Ferrar (Africa, south America, Antarctica)	0.18	(20°W,72°S) ¹ AN	-	-	-	-	-
		(29°W,30°S) ¹ S. Afr.					
CAMP (West Africa, South America, North America)	0.2	(20°W,18°N) ¹ W. Afr.	-	-	-	-	-
		(55°W,10°N) ¹ E. SA					
		(78°W,31°N) ¹ E. NA					
Siberian Trap (Siberia)	0.25	(96°E,73°N) ¹ Rus.	-	-	-	-	-
Yakutsk-Vilyui (Siberia)	0.38	(129°E,63°N) ⁴ Si.	-	-	-	-	
Franklin (northern Canada and Greenland)	0.72	(120°W,75°N) ¹ Can.	Gravity	370 km	+52 mgal	Subcircular <i>d</i> = 90 km	A1, Figure 16; uncertain relation with Franklin LIP
				300 km	+61 mgal	Subcircular <i>d</i> = 135 km	M6, Figure 16; may be linked with Franklin or Mackenzie Event
				612	+132 mgal	Subcircular <i>d</i> = 90 km	DB; Figure 16

Large Igneous Province /Location	Plume Arrival (Ga)	Plume Centre Location (Long, Lat)/ Plume name		Evidence for intrusions	Distance from Plume Centre	Amplitude	Shape and Size	Comments and link to Figures
Mackenzie (northern Canada)	1.27	(116°W,71°N) ¹	Can.	Gravity	135 km	+54 mgal	Elongated 200 × 100 km	M1; Figure 16
					220 km	+59 mgal	Subcircular <i>d</i> = 70 km	M2; Figure 16
					220 km	+78 mgal	Elongated 85 × 50 km	M3; Figure 16
					160 km	+49 mgal	Subcircular <i>d</i> = 70 km	M4; Figure 16
					180 km	+60 mgal	v-shaped 110 × 100 km	M5; Figure 16
					260 km	+52 mgal	Subcircular <i>d</i> = 90 km	M6; Figure 16, uncertain relation with Mackenzie event
					390 km	+61 mgal	Subcircular <i>d</i> = 135 km	A1; Figure 16, may be linked with Franklin event
					320 km	+132 mgal	Subcircular <i>d</i> = 90 km	DB; Figure 16
Kunene-Kibaran (central and eastern Africa)	1.38	(29°E,1.5°S) ⁷	Afr.	Gravity	470 km	+120 mgal	Elongated 220 × 90 km	LV1; Figure 17
					522 km	+50 mgal	Elongated 140 × 80 km	LV2; Figure 17
					560 km	+75 mgal	Elongated 200 × 100 km	LV3; Figure 17

Large Igneous Province /Location	Plume Arrival (Ga)	Plume Centre Location (Long, Lat)/ Plume name	Evidence for intrusions	Distance from Plume Centre	Amplitude	Shape and Size	Comments and link to Figures
Bastar-Cuddapah (India)	1.89	(82°E,15°N) ⁵ In.	Gravity	420 km	+60 mgal	Oval 80 × 50 km	C1; Figure 18, interpreted as a funnel-shaped intrusion in the upper crust; See Grant (1983) and Chatterjee and Bhattacharji (2001)
Ungava- Nipissing (NE Canada)	2.21	(66°W,58°N) ¹ Can.	-	-	-	-	-
Matachewan (southern Canada)	2.48 – 2.45	(81°W,44°N) ⁴ Can.	-	-	-	-	-
Mistassini Southeastern Canada)	2.51	(72°W,50°N) ⁴ Can.	-	-	-	-	-

Figure 13: Bouguer anomaly map the western Deccan Traps, India, with 10 mgal contour lines. White star indicates the Deccan plume centre proposed by Ernst and Buchan 2001a. Red star indicates a potential plume centre based on rift structures observed in the area. D1 – D5 are gravity anomalies in the western Deccan Traps. 1- Narmada-Tapti rift, 2- West coast rift, 3- Cambay rift, 4- Kutch rift.

Figure 14: Magnetic anomaly map near the HALIP plume centre (star), Ellesmere Island, Arctic Canada, with 100 nT contour lines. H1 is a + 850 nT magnetic anomaly at 80 km from the plume centre.

Figure 15: Bouguer anomaly map of the West Africa component of the Paraná-Etendeka LIP. PE1 is a + 60 mgal gravity anomaly near the western coast of Africa. Red star is the proposed plume centre.

Figure 16: Bouguer anomaly map in the Mackenzie (red star) and Franklin (white star – to the north of Banks Island) LIP plume centres, Northwest Territories. Gravity contour lines are drawn at 5 mgal intervals (positive only). M1-M6, A1 and DB are prominent gravity anomalies within the plume centre regions. DB – Darnley Bay.

Figure 17: Bouguer anomaly map of the Lake Victoria region, East Africa, which is a component of the larger Kirene-Kibaran LIP. The inset map shows c. 1380 Ma granitic and mafic-ultramafic intrusions (of the Kabanga-Musongati lineament) at the centre of the swarm. Note that there are anomalies near the inferred plume centre that are belt-like and concave to the east reflect basement geology, e.g., thrust belts (Tack et al. 2010; Fernandez-Alonso et al. 2012). Star indicates a postulated plume centre.

Figure 18: Bouguer anomaly map of the Cuddapah basin in the Dharwar craton, India. C1 is a + 60 mgal, oval-shaped gravity anomaly situated at approximately 400 km from the 1890 Ma plume centre (star).

6.2 Mackenzie LIP (1270 Ma), Northwest Territories, Canada

6.2.1 Geological Overview

The 1270 Ma Mackenzie LIP (Figure 19) is one of the most widespread magmatic episodes to have occurred on Earth, with an aerial extent estimated at 2.7 Mkm^2 (Fahrig and Jones, 1969; Fahrig, 1987). Mackenzie magmatism is generally attributed to the arrival of a mantle plume at the base of the lithosphere centered on Victoria Island, Northwest Territories, in the southwest Canadian Archipelago (e.g., LeCheminant and Heaman, 1989). Victoria Island is largely covered by Paleozoic sedimentary rocks, with the exception of a number of Precambrian intrusive and volcanic rocks within the Minto Inlier (Figure 20). The Minto Inlier is a 300 km-long by 150 km-wide belt across central Victoria Island that hosts scattered gabbroic sills and their extrusive equivalents belonging to the much younger 725 Ma Franklin LIP, with a plume centre to the north of Banks Island (Buchan et al., 2010; Bedard et al., 2012; Rainbird et al., 2013).

The Mackenzie LIP is distributed across most of the Canadian Shield and consists of: the Coppermine River flood basalts, the mafic-ultramafic Muskox intrusion, numerous sills and layered intrusions, and the Mackenzie giant radiating dyke swarm. The latter is the largest dyke swarm on Earth, extending more than 2000 km from its focus on Victoria Island with a 100° of arc (Fahrig, 1987; Ernst et al., 2005). High precision dating (U-Pb on baddeleyite; LeCheminant and Heaman, 1989) shows that all dated dykes were emplaced at $1267 \pm 2 \text{ Ma}$, and that the entire event occurred within 5 million years.

The shallow mafic-ultramafic Muskox intrusion was emplaced at $1270 \pm 4 \text{ Ma}$ (U-Pb on zircon; LeCheminant and Heaman, 1989) and is interpreted to be an early-stage component of Mackenzie magmatism. The intrusion is exposed to the south of Victoria Island on the Arctic mainland, where it

extends north-south for 125 km with a variable width from 11 km in the north to 100 m in the south. It plunges northward at 3° to 5° beneath the Proterozoic Dismal Lake sedimentary rocks for about 250 km towards the north (e.g., Gittings, 2001), towards a gravity anomaly thought to mark an associated layered intrusion. Being the only known exposure of a Mackenzie-aged mafic-ultramafic layered intrusion, a summary of the structure and composition of the Muskox intrusion is provided here.

The Muskox intrusion is dyke-like in plan-view and funnel-shaped in cross section (**Figure 21a** and **21b**; Smith and Kapp, 1963). It is divided into four main zones: the feeder zone, marginal zones, central layered series and the upper border group. The feeder has near-vertical walls composed of bronzite gabbro and picrite. The marginal zones run parallel to the inward dipping walls and range from 60 to 365 meters in thickness, along which nickel-copper sulfides and pyrrhotite occur. The central layered series is composed of 38 main layers that range in thickness from 3 to 560 meters, with a total thickness of ~2.5 km, which are composed of alternating layers of serpentinized dunite, peridotite, feldspathic peridotite, picrite, olivine clinopyroxenite, websterite, orthopyroxenite, troctolite, olivine gabbro, gabbro, norite and anorthositic gabbro. Lastly, the upper border group is a zone in which granophyric intergrowths and quartz content increase upward at the expense of mafic minerals (Smith and Kapp, 1963).

To the north of the Muskox intrusion, gravity anomalies circumscribe the plume centre at an average distance of 250 km from the plume centre, and are the focus of the present study. These occur along a boundary marked by a change in magma flow-direction (Fahrig, 1987; Ernst and Baragar, 1992; Baragar et al., 1996; Ernst and Buchan, 1997). They propose that there is a localized, relatively small area (500 km in diameter) at the centre of the Mackenzie dyke swarm is a through

which mainly tholeiitic magma entered vertically into the lithosphere. Beyond this point, anisotropy of magnetic susceptibility (AMS) studies show horizontal flow of magma (Ernst and Baragar, 1992). In the present study, these anomalies are modelled using gravity and magnetic data, and their spatial relationship with the Mackenzie plume centre and with other components of the LIP plumbing system, particular with respect to the Mackenzie radiating dyke swarm and the Muskox intrusion, are also investigated.

Figure 19: Map of the 1270 Ma Mackenzie LIP, Northwest Territories, Canada. The plume centre (star) lies at the focus of the Mackenzie giant radiating dyke swarm (red lines). Six layered intrusions identified from gravity anomalies partially circumscribe the plume centre at an average distance of 250 km from the plume centre. Note that intrusion VI is included here but was not one of the five identified by LeCheminant and Heaman (1989) and Baragar et al. (1996). An additional anomaly to the north-west is not shown above but is shown and discussed in Figure 22. CH = Coppermine homocline; M = Muskox intrusion; Cb = Coppermine River basalts; Eb = Ekalluk basalts; DB = Darnley Bay. Modified from Buchan et al. (2010).

Bedrock Geology

Cenozoic

Neogene sedimentary rocks

Mesozoic

Cretaceous-Tertiary sedimentary rocks

Paleozoic

Silurian-Devonian marine sedimentary rocks

Devonian nonmarine sedimentary rocks

Cambrian-Silurian sedimentary rocks

Precambrian

Mesoproterozoic-Neoproterozoic sedimentary rocks

Neoproterozoic mafic intrusive rocks - diorite, gabbro

Proterozoic granitoid rocks

Archean-Proterozoic sedimentary and volcanic rocks

Archean-Proterozoic mafic volcanic rocks

Archean volcanic rocks

Archean granitoid rocks

Archean metamorphic rocks

Figure 20: Bedrock geology map of Victoria and Banks Islands, and the northern Canadian Arctic Mainland. Modified after Wheeler (1996).

Figure 21: Schematic diagram of the Muskox intrusion. a) Plan view after Barnes and Francis (1995) and Irvine (1988), and b) side view showing its funnel-shape and internal layering after Smith and Kapp (1963).

6.2.2 Geophysics in the Mackenzie Plume Centre Region

Eight prominent gravity anomalies are situated in the Mackenzie plume centre region that range in size from 35 to 200 km in diameter, with amplitudes between + 50 and + 130 mgal relative to the background (Figure 22; Table 7). It is clear from bedrock geology (Figure 23) that the anomalous masses are not apparent at the surface and are that these gravity anomalies are caused by deeper sources. The largest anomaly in the region is the + 132 mgal gravity anomaly at Darnley Bay (DB, Figure 22), with a coincident + 1350 nT magnetic anomaly. The anomaly is about 100 km in diameter and is interpreted through geophysical modelling to be the expression of a deep-seated mafic-ultramafic layered intrusion potentially linked to the 720 Ma Franklin or 1270 Ma Mackenzie LIPs; however the age and geometry of this intrusion are still unknown as drillcores have not yet intercepted the intrusion (Reford, 2012).

Given the circumferential pattern of anomalies M1 to M5 and their distribution at approximately 40° to 60° intervals around the plume centre, we consider two additional + 52 and + 61 mgal anomalies to the north and northwest (M6 and A1, Figure 22, respectively) that are similarly positioned around the plume centre. These were not identified by LeCheminant and Heaman (1989) or Baragar et al. (1996) as being related to the Mackenzie LIP, but may be a continuation of the Mackenzie igneous bodies towards the north. Anomalies M6 and A1 additionally have similar dimensions and amplitudes as M1 to M5, which is suggestive of a similar type of causative body as those inferred for M1-M5, and therefore is an indication that there is a link with Mackenzie magmatism. M6, in particular, continues the circumferential pattern and provides supporting evidence towards a complete 360° arrangement of intrusions circumscribing the plume centre. On the other hand, the relationship between the Mackenzie intrusions and A1 is somewhat

less clear. A1 is similar in size and amplitude as anomalies M1-M6, but is offset from the others, and may be a component of the 1270 Ma Mackenzie event, or the 720 Ma Franklin LIP to the north, which has a plume centre near Banks Island, Nunavut.

In the surrounding areas, regional gravity maps show a transition from gravity highs to lows that coincide with the boundary of the Amundsen Embayment, which is a series of stratified Precambrian and Palaeozoic rocks occurring in an oval synclinal basin and whose edges are on the Arctic mainland and the central part of Victoria Island (Figure 24; Jefferson et al., 1988; Rainbird, 1992). Consequently, positive gravity anomalies on the southern and eastern edges of the plume centre are better defined due to the strong contrast with the gravity low in the south-eastern regions (Figure 22). In contrast, the anomalies become progressively less defined towards the north-west, with M6 and A1 being the least well-defined. The anomalies are located over 310° around the plume centre, focused mainly on the well-exposed southern half of the plume centre region, but it remains unclear if the mafic bodies completely circumscribe the plume centre and their geophysical signatures are simply obscured by noise to the north-west.

In order to compare gravity and magnetic anomalies in the region, the magnetic anomaly map is overlain with gravity anomaly contour lines (Figure 25). Most of the gravity anomalies are coincident with positive magnetic anomalies, indicating that the Mackenzie intrusions have both a high density and a high magnetic susceptibility. These magnetic anomalies are significantly less well-defined than the gravity anomalies, which indicates that the magnetic minerals are not evenly distributed throughout the intrusions. The exception is at Darnley Bay to the west, where both the gravity and magnetic anomalies are exceptionally well-defined and overlap.

Tangential receiver functions indicate the presence of a thick layer of intermediate shear wave velocity (4.0 – 4.3 km/s) at the focal region of the Mackenzie dyke swarm that is consistent with mafic lower-crustal material at depths of 35 to 55 km (Darbyshire, 2003). Darbyshire (2003) propose that the anomalous layer may be magmatic underplating caused by the presence of the Mackenzie plume. Their interpretation is consistent with magnetic data that shows a prominent, 300 km-wide magnetic anomaly at the focus of the Mackenzie swarm that also inferred in the present study to be caused by the presence of underplated magma (Figure 25).

Figure 22: Bouguer anomaly map near the Mackenzie plume centre (star), Victoria Island, showing eight prominent gravity anomalies in the plume centre region. These are: anomalies M1 to M5 interpreted as layered intrusions linked with the Mackenzie LIP (LeCheminant and Heaman, 1989; Baragar et al., 1996), the Darnley Bay anomaly to the west (DB) and two additional anomalies that we herein consider in terms of Mackenzie magmatism: M6 and A1. Gravity contour lines are drawn at 5 mgal intervals and are indicated as fine black lines. Profile lines A-A', B-B', C-C' and D-D' are selected for modelling (section 6.2.3).

Figure 23: Simplified geological map in the vicinity of the Mackenzie plume centre (star) on Victoria Island, NWT, with contour lines showing the location of the gravity anomalies I-VI, A1 and DB shown in Figure 22. Geology map after Garrity and Soller (2009). Dyke swarms are from Buchan and Ernst (2013).

Figure 24: The Amundsen Embayment, which comprises relatively undisturbed Proterozoic sedimentary rocks intruded by mafic sills and dykes. From Jefferson et al. (1988).

Figure 25: Magnetic anomaly map near the Mackenzie plume centre (star) with gravity anomalies M1 through M6 indicated by contour lines. Profile lines A-A', B-B', C-C' and D-D' are selected for modelling (section 6.2.3).

6.2.3 Modelling

Many have speculated on the existence of the Mackenzie mafic-ultramafic intrusions, but this is the first study where modelling is conducted in order to quantitatively assess their dimensions, rock property values, and their positioning within the crust. Modelling is completed along four profile lines that intersect anomalies M1-M5 (Figure 22 and 25) and the preferred models are presented here. Modelling across anomaly M6 was also considered, but the anomaly is located in a region of higher background “noise” that affected the modelling procedure.

Profile line A-A' (Figure 26) intersects a + 50 mgal gravity anomaly at M1, located at approximately 150 km east of the Mackenzie plume centre. The gravity anomaly extends for nearly 200 km in the north-south direction and 100 km in the east-west direction. Gravity data are dominated by long-wavelength components while magnetic data have both long and short wavelength components (Figure 26). The long wavelength signals at the western end of the profile coincide and likely share a common origin. To the east, a long wavelength gravity low is roughly coincident with a magnetic plateau. The gravity low on the eastern side indicates a thick sedimentary succession; however it is unlikely that the elevated magnetic signal is caused by this same formation. It is much more likely that the sedimentary basin was underlain or intruded by mafic sills during Mackenzie magmatism, and so we infer the presence of a sill in, or beneath, the basin; however the exact depth of this sill remains difficult to constrain without supporting seismic data. The long wavelength components of both the gravity and magnetic data to the west are inferred to be caused by magmatic underplating.

Modelling of gravity and magnetic data indicates the presence of a 7 km thick intrusion at a depth of 18 km, which is located in the middle crust. Density estimates of 3.0 to 3.3 g/cm³ are

consistent with mafic to ultramafic compositions, and magnetic susceptibility estimates indicate moderate magnetic mineral content. Modelling along the profile line indicates that the intrusion is approximately 30 km wide in the east-west direction. From the extent of the gravity anomaly in the north-south directions, it is likely that the intrusion extends for nearly 100 km in the N-S direction, perpendicular to line A-A'.

Figure 26: Profile line A-A' that intersects anomaly M1 (Figure 22 and 25). The + 54 mgal gravity anomaly, measured relative to the mean background value, is situated at ~150 km northeast of the Mackenzie plume centre. Magnetic (top) and gravity (middle) data are well-reproduced by a 30 km × 120 km × 7 km mafic-ultramafic intrusion at a depth of 15 km in the middle crust. Magmatic underplating at the base of the crust caused by the presence of the Mackenzie plume reproduces the long-wavelength magnetic and gravity signals to the SW. Sills possibly related to the Mackenzie LIP underlie (or are situated within) a ~ 5 km thick sedimentary basin to the NE.

Profile line B-B' (Figure 27) intersects a + 59 mgal gravity anomaly at M2, located at just over 200 km from the plume centre. The anomaly is subcircular with a diameter of 70 km, and coincides with a + 230 nT magnetic anomaly. Gravity and magnetic anomalies mostly coincide along the profile line, however a short wavelength magnetic anomaly occurs towards the south-east. Given the focus on the large intrusion that produces the gravity anomaly observed at M2, this anomaly is not considered for current modelling purposes.

Modelling indicates the presence of a 10–20 km thick, predominantly mafic to ultramafic, funnel-shaped intrusion at a limiting depth of ~15 km with moderate to high magnetic mineral content. Magma is interpreted to have been supplied from a large chamber at the base of the crust, likely the same chamber that fed all intrusions in the region, by a feeder dyke at the base of the intrusion. The dyke extends northwards and is connected to the intrusion at M1, as seen from a linear gravity high connecting the two anomalies M1 and M2. The depth to which the feeder dyke extends is unclear, however, because of the high-density rock above it that obscures the signal and makes it difficult to constrain.

Figure 27: Profile line B-B' that intersects anomaly M2 (Figure 22 and 25). Observed magnetic (top) and gravity (middle) data are indicated by the black dotted line, and the response of the model is indicated by solid black lines. A ~ 10-km-thick funnel-shaped intrusion is modelled at a depth of 15 km in the middle-lower crust and estimates density values that are consistent with mafic and ultramafic rock compositions.

To the west of the plume centre, there are three gravity highs: the +60 mgal anomaly at M3, the +49 mgal anomaly at M4 and the +78 mgal anomaly at M5 (Figure 22), all of which coincide with magnetic anomalies. Relative to the eastern and southern sides, the geology on the western and northern sides of the plume centre is significantly more complex, which is directly reflected by a more complex pattern on the geophysical anomaly maps (higher background noise). In order to intersect the anomalies M3 to M5 while avoiding other anomalies, profiles lines C-C' and D-D' are selected for modelling. C-C' intersects anomaly M4 and line D-D' intersects anomalies M3, M4 and M5 perpendicular to C-C'.

Modelling across line C-C' (Figure 28) suggests that the anomaly is produced by a 6-8 km thick, 60 km long, sill-like intrusion at a depth of 13 km, positioned in the upper crust. Given the subcircular shape of its associated gravity anomaly, the intrusion is inferred to be symmetric in all directions. Density estimates of 3.0 g/cm^3 suggest that the intrusion is mainly mafic in composition, with moderate magnetic mineral content reflected by magnetic susceptibilities of 0.004 to 0.009 cgs (0.05 – 0.11 SI).

Modelling across line D-D' indicates three sill-like intrusions at depths of 12-15 km. These include the intrusion M4 shown in Figure 28 and intrusions at M3 and M5 that are similarly positioned within the crust as intrusion M4 and have similar shapes and properties (Figure 29). The intrusions appear to be linked at depth via a common feeder dyke, which is apparent from gravity maps as a narrow gravity high linking the three intrusions, similar to the gravity high connecting M1 and M2 (Figure 22). The downward extent of the dyke-like intrusion, which likely acted as the feeder system for the sill-like intrusions at upper crustal levels, is difficult to resolve due to a lack in density

contrast at depth and the dyke-like intrusion may continue deeper into the crust than the model indicates.

Figure 28: Profile line C-C' that intersects anomaly M4 (Figure 22 and 25). Observed magnetic (top) and gravity (middle) data are indicated by black dots, and the responses of the model are indicated by solid black lines.

Figure 29: Profile line D-D's intersecting anomalies M3, M4 and M5 (Figure 22 and 25).

6.2.4 Discussion

We present the first study that quantitatively assesses the Mackenzie gravity anomalies and provides depth, dimensions and physical property estimates through geophysical modelling. Modelling indicates that the Mackenzie region hosts a combination of mafic-ultramafic sill-like and dyke-like layered intrusions, with moderate to high magnetic mineral content, reflected by typical magnetic susceptibilities of 0.006 to 0.01 cgs (0.08 – 0.13 SI), positioned at middle to upper crustal levels (i.e. 10 to 20 km depths). The high densities are most likely caused by gabbroic mafic rocks and peridotite-dominated ultramafic rocks, with varying degrees of magnetite throughout the intrusions. From their link with the 1270 ± 4 Ma Muskox intrusion and the slightly younger Mackenzie radiating dyke swarm with available ages of 1267 ± 2 Ma, these intrusions were likely emplaced during the initial stage of Mackenzie magmatism.

Modelling indicates that the intrusions are discrete at upper levels but are likely joined at the base. This is also apparent from gravity lineaments that join anomalies M3, M4, and M5, and also anomaly M1 with M2. Here, magma is inferred to have been fed from either vertical-near vertical circumferential feeder dykes or intruded along faults, where it pooled at mid to upper levels in the crust, forming individual intrusions in the crust. The gravity high between the intrusions on the east side (M1, M2) with those of the west side (M3, M4, and M5) is not resolved at the present scale, but it is apparent that the gravity high lineaments curve towards the south from M2 and M3. It is possible circumferential fracturing or faulting would have occurred, but a pre-existing weakness in the crust channeled magma southward towards the Muskox intrusion.

It is expected that both radial and circumferential fractures would have been produced during the uplift/subsidence phases. The Mackenzie radiating dyke swarm was emplaced as a result

of radial stresses associated with uplift, while a circumferential fault system would have formed during the subsequent collapse (Baragar et al., 1996). Although no circumferential dykes are observed at the surface, evidence towards circumferential features includes the Mackenzie layered intrusions identified from gravity, in addition to their positioning that coincides with gravity lineaments that also circumscribe the plume centre that could represent a buried circumferential dyke swarm. In this case, the intrusions would lie at the intersection of the circumferential and radial dyke swarms. The combination of circumferential and radial fractures likely led to magma channeling along weak spots in the crust, leading to a discrete number of intrusions that are more or less equally spaced at 40-60° intervals. This is most clearly seen in the schematic diagram of the region shown in Figure 30, which is based on the initial model proposed by Baragar et al. (1996). As depicted in the model, the Mackenzie intrusions are fed via circumferential and radial fractures. The magma being channeled into the chambers at M1 – M5 spread laterally from these source points, eventually forming individual subswarms that collectively represent the Mackenzie radiating dyke swarm. The modelling results and interpretation from the present study are in agreement with the initial insights by Baragar et al. (1996), who suggested that magma ascended through faulting induced from stretching of the crust during uplift that facilitated the magma's ascent, leading to the production of individual magma chambers, and to their subswarms (Figure 31).

Although additional smaller intrusions are not generally mapped at the present scale, secondary intrusions may be present in the vicinity of the intrusions at M1-M6 and may be detected based on their relation with the large intrusions circumscribing the plume centre. A survey of radial gravity high lineaments that may represent feeder systems similar to the one that connects the Muskox intrusion and the intrusion at M3 highlights several intriguing gravity anomalies nearby. Linear

gravity highs are discernible and are aligned from the plume centre outwards and coincide with the intrusions at M1-M6 (Figure 32). For example, this is observed at M2 where a narrow gravity high extends from M2 towards gravity highs at M2a and M2b. Although these are not immediately apparent from regional-scale surveys, they may be attributed to near-surface exploration targets similar to the Muskox intrusion.

Figure 30: Schematic diagram of the Mackenzie mafic bodies in the upper to middle crust (grey bodies). Colored map shows the same Bouguer anomaly map as in Figure 22. In agreement with models proposed by Baragar et al. (1996), we infer that the Mackenzie intrusions were fed along a circumferential dyke system (grey) and radial fractures formed during extension that channeled magma from the source areas in the underlying mantle to more-or-less equally spaced magma chambers circumscribing the plume centre at an average distance of 200 km from the centre. Each magma chamber produced individual subswarms (red) as magma extended laterally through the crust. (1 square = 10 km).

Figure 31: Model proposed by Baragar et al. (1996) in which plume-induced uplift led to graben collapse near the uplift core that facilitated the development of individual magma chambers, each of which fed its own radial dyke subswarm. From Baragar et al. (1996).

Figure 32: Bouguer anomaly map – Victoria Island. M1- M5 (and possibly M6) are gravity anomalies modelled as intrusions around the Mackenzie plume centre. The Muskox intrusion (M) is linked within the intrusion at M3 observed here as a narrow gravity high aligned away from the plume centre. M1a, M2a,b, M41, M5b are additional targets for exploration through higher-resolution surveys that are potentially similar to the Muskox intrusion in size and depth.

6.3 Kunene-Kibaran LIP (c. 1380 Ma), East Africa

6.3.1 Geology of the Lake Victoria Region

The c. 1380 Ma Kunene-Kibaran LIP (Figure 33) is a major magmatic event in central Africa related to the breakup of the Columbia/Nuna supercontinent (e.g. Meert, 2012; Evans, 2013; Pisarevsky et al. 2014), with components distributed across the Greater Congo Craton (GCC) (Ernst et al. 2008; Tack et al., 2010; Mäkitie et al., 2014). Fragments of the LIP are currently recognized in three regions of the GCC (Figure 33): 1) the mafic-ultramafic intrusions of the Kabanga-Musongati lineament, and associated gabbro-norite sills and S-type granites hosted within the Karagwe-Ankole Belt (KAB) in the northeast GCC, 2) the mafic-intermediate Kibara Belt (KIB) in the southeast GCC, and 3) the Kunene layered complex with its associated granites and dykes in the southwest GCC.

This study is focused on the Lake Victoria region (Figure 34a) in East Africa at the intersection of Kenya, Uganda and Tanzania, and is centrally located between the Western and Eastern Branches of the East African Rift System (EARS). A detailed review of the geological setting is provided in order to properly interpret the gravity and magnetic anomalies detailed in section 6.3.2.

In the Lake Victoria region, there is a 100 km wide semi-circular mafic dyke swarm which is hosted within the Paleoproterozoic Rwenzori Fold Belt (RFB), and that circumscribes coeval mafic-ultramafic and granitic intrusions hosted in the KAB (Figure 34a, Mäkitie et al., 2014). Arcuate lineaments were first recognized by Batherham et al. (1983) and Chavez Gomez (2000); however it was not until recently that the full extent of the swarm became apparent from extensive aeromagnetic surveys. A continuation of the swarm is identified from aeromagnetic data on the southern edge of Lake Victoria, hosted in the Archean Tanzania Craton, and correlated across the lake where aeromagnetic surveys are lacking, forming a nearly 180° semi-circular dyke swarm with

an outer radius of roughly 500 km (Figure 34b; Mäkitie et al., 2014). Together, these dykes form the Lake Victoria Dyke Swarm (LVDS). Sm-Nd mineral ages of 1368 ± 41 Ma and 1374 ± 42 Ma (Mäkitie et al., 2014) for two dykes belonging to the swarm indicate that these belong to the larger ca. 1380 Ma Kunene-Kibaran event (e.g., Tack et al., 2010), however it remains unclear how the LVDS and nearby coeval intrusive rocks in the Lake Victoria region were emplaced, nor how they relate to the larger c. 1380 igneous event that extends across the GCC and makes up the Kunene-Kibaran LIP. It is also unknown whether the circular swarm continues to the west and defines a complete 360° circumferential swarm.

The Rwenzori Fold Belt (RFB) that hosts the northern portion of the LVDS is situated between the Archean Uganda block and the Mesoproterozoic Karagwe-Ankole Belt (KAB), (Figure 34). The KAB was formed over the span of roughly 410 million years, between 1.78 and 1.37 Ga (Fernandez-Alonso et al., 2012). The 1.38 Ga dolerite dykes of the LVDS are coeval with the upper sequence of the KAB that Mäkitie et al. (2014) propose was once capped by now eroded flood basalts. The KAB hosts a number of 1.36 – 1.38 Ga granites and mafic-ultramafic intrusions belonging to the Kabanga-Musongati (KM) alignment (Tack et al., 2008) with which the LVDS is similarly coeval (e.g. Maier et al., 2010; Mäkitie et al., 2014). Together, these form the c. 1380 Ma magmatism in the Lake Victoria region, which is part of the broader Kunene-Kibaran LIP (Figure 33), (Tack et al., 2008).

Roughly two thirds of Uganda is underlain by Precambrian bedrock. The Archean craton underlies most of the central and northern portions of Uganda, with inliers occurring to the south and southwest within the Proterozoic Fold Belt (Hester, 2009; Mänttari et al., 2011, 2013). This study focuses on regions to the north and south of Lake Victoria (Figure 35 and 36). The northern region is largely made up of a portion of the Paleoproterozoic Rwenzori Fold Belt (RFB), along with a

portion of the LVDS and various intrusive granites, Archean basement complex and, furthest to the east, intrusive granites and volcanic rocks of Precambrian ages. Most of the region is covered by Quaternary sediments, with various Tertiary sediments in eastern Uganda and larger concentrations of Proterozoic sediments in south and southeast Uganda.

Directly to the south of Lake Victoria is the main part of the Tanzania craton that underlies a large part of the Central Plateau of Tanzania (Taylor, 2009). The southern-central parts of the Tanzania craton contain medium to high-grade gneiss-migmatites (Goodwin, 1996), as well as the oldest rocks in the region belong to the Archean Dodoman System, which is a system of highly metamorphosed and migmatized sedimentary and minor volcanic rocks confined to central Tanzania (Taylor, 2009). The southern and central regions of the craton are also widely intruded by 2.6 Ga granitoids intrusions (Goodwin, 1996). To the north, the east-trending Nyanzian greenstone belts are largely intruded by 2.8 Ga granitoids and unconformably overlain by the Kavirondian system of weakly metamorphosed sediments intruded by 2.5 Ga granitoids, which are confined to the Lake Victoria region and make up the northern part of the Archean Tanzanian craton (Barth, 1990; Goodwin, 1996; Hester, 1998; Taylor, 2009).

As of yet, there is no observed continuation of the swarm to the west. However limited data is available to the west (in Burundi, Rwanda and Democratic Republic of Congo), due mostly to political instability in these regions. Nonetheless, on the basis of its remarkable 180° arcuate dyke swarm the LVDS appears to be unique globally and, although other dykes swarms have been observed to change orientation (for example, the Mackenzie swarm that changes direction as a response to a regional stress regime), the drastic arc of the LVDS is not likely to have been formed through subsequent deformational processes and, instead, is much more likely to have been emplaced as a

primary semi-circular or circular swarm. Here we present evidence for large intrusions located on the outer periphery of the LVDS, in addition to evidence for triple junction rifting that supports a central plume location. We also consider the potential implications of these intrusions and triple junction rifting with regard to the current models for the formation of the Lake Victoria portion of the Kunene-Kibaran LIP.

Figure 33: General geology of the Greater Congo Craton (GCC) showing recognized components of the Kunene-Kibaran LIP, including fragments in the Lake Victoria region (boxed outline). KIB, Kibara; KAB, Karagwe-Ankole Belt. Craton blocks are labeled: Gabon (GC), Angola (AB), Kasai (KB), Tanzania (TC), Uganda (UB), and the Northeast Congo (NEC). Figure from Mäkitie et al. (2014).

Figure 34: a) Geological map focused on the Lake Victoria region showing the c. 1380 Ga dolerite dykes (green) hosted in the Archean-aged Uganda Block and Tanzania Craton. b) Aeromagnetic map of the Lake Victoria region, showing the dyke swarm on both edges of the Lake in Southwest Uganda and Northwest Tanzania. From Mäkitie et al. (2014).

Figure 35: General geology map of Uganda. Red box indicates the extent of Figure 34 and the green box indicates the region of interest to this study. Modified after SEAMIC, 2004 (Southern and East African Mineral Centre).

Figure 36: General geology map of Tanzania. Red box indicates the extent of Figure 34 and the green box indicates the region of interest to this study. From Taylor (2009), after Hester (1998).

6.3.2 Geophysics in the Lake Victoria Region

Bouguer gravity data spanning the Lake Victoria region (Figure 37) delineate three subcircular to elongate + 50 to + 80 mgal gravity anomalies with dimensions of approximately 100 km × 200 km (LV1, LV2 and LV3). These regional-scale gravity anomalies are situated on the outer periphery of the LVDS (burgundy lines, Figure 37), at just over 500 km from a postulated plume at the centre of the LVDS, and also follow the arcuate trend of the LVDS.

It is clear from the bedrock geology that the anomalous masses are not apparent at the surface (Figure 38 and 39), signifying that the gravity anomalies are produced from unknown sources deeper in the crust. Anomalies LV1 and LV2 are situated within the Archean-aged Uganda block and Tanzania craton, respectively. Given their large sizes and amplitudes, we can confidently attribute their existence to large bodies emplaced during a large magmatic event. This, along with their positioning on the outer periphery of the LVDS, suggest that the anomalies are linked with the same event that produced the LVDS, the inner series of mafic-ultramafic and granitic intrusions all in the KAB node of the regional Kunene-Kibaran LIP. LV3, on the other hand, is situated along the western branch of the East African Rift System (EARS) (Figure 37). The source for the gravity anomaly LV3 is therefore less clear than those at LV1 and LV2. Nevertheless, the anomaly LV3 is similar both in size and amplitude, as well as being similarly positioned along the outer periphery of the LVDS and continuing the arcuate trend of the LVDS, suggesting that its origin is similar to LV1 and LV2. We therefore investigate anomalies LV1, LV2 and LV3 as potential components of the Kunene-Kibaran LIP plumbing system but focus our study on anomalies LV1 and LV2 as we can be more confident about their origin.

We additionally note two linear gravity highs extending through LV1 and LV2 which are oriented along R1 and R2 as indicated in Figure 37. These lineaments may indicate an extension of the intrusions at LV1 and LV2, namely that these intrusions are considerably elongated, or given that they are oriented towards the centre of the LVDS, this suggests that R1 and R2 may represent the geophysical expression of rifting with an intersection at the centre of the swarm (as in the pattern of triple junction rifting associated with a mantle plume).

We consider magnetic anomaly maps in the Lake Victoria region (Figure 40) in order to determine if the gravity anomalies are coincident with magnetic anomalies. In order to jointly interpret the gravity and magnetic data, the magnetic data are reduced to the pole and superimposed with contour lines representing the positive gravity anomalies LV1 and LV2 (Figure 41). Reduction to the pole transforms the observed magnetic field to what the field would look like at the magnetic pole. This is particularly effective in low-latitude areas, such as the Lake Victoria region, and aids in interpretation of anomaly maxima in the reduced to pole data which will be more centrally located over the body. This does assume, however, that no remanent magnetization is present in the causative body.

The magnetic data near Lake Victoria are strongly reflective of the complex geology of the Uganda and Tanzania cratons. In particular, E-W trends in regional magnetic data are apparent and reveal the presence of magnetic E-W trending greenstone belts in the Lake Victoria region and numerous banded iron formations throughout the entire region, as previously noted by Stephenson, 1981. The gravity anomalies at LV1 and LV2 do not appear to have obviously apparent magnetic signals associated with them. This is particularly true to the south of Lake Victoria, where LV2 underlies extensive magnetic, east-west trending greenstone belts.

The correlation between the gravity and magnetic signals at LV1 is less clear. The north-western edge of the gravity high corresponds with a magnetic high, while the south-western edge of the gravity anomaly corresponds with a magnetic low. This offset between gravity and magnetic anomalies suggests that remanent magnetization may be present in the source body. We therefore consider Curie depths near the study area (Kuria, 2011) during the modelling process (detailed further in section 6.3.3); the Curie isotherm corresponds to the maximum depth at which remanent magnetization can be preserved (e.g., Wasilewski and Mayhew, 1992).

Figure 37: Bouguer anomaly map centered on Lake Victoria and LVDS (burgundy lines) in East Africa. Countries boundaries and coastlines are indicated in light grey, and major faults are indicated in black, marking the southern termination of the East African Rift System (EARS), after Barberi et al., (1982). LV1, LV2 and LV3 are +58 mgal, +70 and + 75 mgal gravity anomalies, respectively, and R1 and R2 (indicated by dotted black lines) are potential rift structures, all of which are investigated in the present study as belonging to the ca. 1380 Ma Kunene-Kibaran LIP. A-A' and B-B' are profile lines selected for modelling (section 6.3.3).

Geology of Uganda

Quaternary

- Sedimentary rocks
- Volcanics and Metavolcanics
- Shales and Quartzites

Tertiary

- Carbonatites and Syenites
- Volcanics

Precambrian

- Conglomerates, sandstones, and shales
- Argillites and Arenites
- Phylites and Schists
- Gneises
- Intrusive Granites and Granitoids
- Schists, Amphibolites, Quartzites, Marbles and Granulites
- Volcanics and metavolcanics
- Archean Basement Complex
- Cataclasites

----- Country Borders

Figure 38: Bedrock geology map of Uganda with 10 mgal contour lines showing the location of the gravity anomalies LV1 and R1. Geology map modified after SEAMIC, 2004 (Southern and East African Mineral Centre).

Figure 40: Magnetic anomaly map *before* reduction to the pole, with gravity contour lines outlining the gravity anomalies LV1 and LV2 (fine black lines) and major faults locating the boundaries of the EARS (dark grey lines).

Figure 41: Magnetic anomaly map reduced to the pole, with gravity contour lines outlining the gravity anomalies LV1 and LV2 (fine black lines) and major faults locating the boundaries of the EARS (dark grey lines).

6.3.3 Modelling

Profile lines A-A' and B-B' (Figure 37) are selected for modelling across LV1 and LV2. The + 120 mgal gravity anomaly near LV1 is positioned at 530 km from the centre of the LVDS and the + 50 mgal anomaly near LV2 is located at 490 km from the centre. Each is elongate with dimensions of 220 km x 90 km and 140 × 80 km, with a maximum peak that coincides with a bulge in the anomaly (Figure 37). From the geometry of the anomalies, separate sources are considered for the subcircular anomalies and for the elongate gravity highs aligned along R1 and R2 which are potentially linked to rifting. Henceforth, LV1 and LV2 are used to refer to the circular component of the gravity anomalies and R1 and R2 refer to the elongate component. Lines A-A' and B-B' are selected across LV1 and LV2 and are perpendicular to R1 and R2 to best model the bodies at LV1 and LV2 without interference from R1 and R2.

The anomaly LV1 is subcircular with a diameter of 100 km. The circular shape of the anomaly is suggestive of radially symmetric density distribution as the causative body. The magnetic data are less directly interpreted as the magnetic anomaly does not coincide with the positive gravity anomaly (Figure 40 and 41). Nevertheless, we infer that the variation from magnetic positive to magnetic negative across the gravity anomaly (Figure 41) is caused by remanent magnetization within the host rock. This is in agreement with Curie depth estimates (Kuria, 2011) for a study area nearby (250 km to the east; Figure 42), that indicate that the depth to which we would expect remanent magnetization to be preserved extends to deep crustal levels at approximately 30 km depths.

The long-wavelength gravity and magnetic anomalies along A-A' are well-reproduced by a 5 km-thick, sill-like body at mid to lower crust levels (Figure 43). Density estimates of 3.1 g/cm³ and 3.4

g/cm³ are consistent with mafic and ultramafic rocks. No direct remanent magnetization measurements of the intrusive body exist, nor are there any records of remanent magnetization studies that we are aware of that have been conducted on nearby ultramafic rocks belonging to the event that would provide an estimate of the remanence component in the rocks. Nevertheless, the magnetic data along A-A' are best reproduced by a body with a moderate induced magnetization component and a moderate - high remanent magnetization component with reversed polarity and inclination of 38° and declination of 22°.

Figure 42: Curie point depth estimates for central southern Kenya Rift from Kuria (2011).

Figure 43: Cross section model along A-A' (Figure 37). The lower panel shows the preferred model for the LV1 anomaly, where a 5 km thick, sill-like mafic-ultramafic body sits at a depth of 20 km at the base of the middle crust. The top and middle panels show the magnetic and gravity responses of the model (solid black lines), the observed (dotted black lines) magnetic and gravity data, and the misfit between the two (red lines), respectively. Note, density is in units of g/cm^3 and magnetic susceptibility is in cgs units.

The long-wavelength gravity anomaly at LV2 along profile line B-B' is well-reproduced by 5 km-thick sill-like intrusion at a depth of 18 km in the middle crust extends for nearly 80 km in the NE-SW direction along line B-B' (Figure 44). The magnetic data, on the other hand, exhibit shorter wavelength signals (~ 50 km) than what would be expected for an intrusion of this scale positioned in the middle crust (~ 220 km). The lack of knowledge pertaining to the presence of remanent magnetization in the buried rocks adds uncertainty to the interpretation of the magnetic data, but we do note that the magnetic trend in the region tends to be east-west and reflects the east-west trending greenstone belts in northern Tanzania (Figure 41), which is also apparent at LV2. It is clear that the magnetic signal observed at LV2 is not produced by the same body that produces the large gravity anomaly. We therefore present the best attempt at reproducing the magnetic signal (Figure 44) to emphasize that the magnetic signal cannot be produced by the intrusion. The preferred model (Figure 45) is modelled using gravity data only.

Figure 44: Cross section model along B-B' (Figure 37). The lower panel shows the preferred model for the LV2 anomaly, where a 5 km thick, sill-like mafic-ultramafic body sits at a depth of 18 km in the middle crust. The top and middle panels show the magnetic and gravity responses of the model (solid black lines), the observed (dotted black lines) magnetic and gravity data, and the error between the two (red lines), respectively. Note that the short-wavelength magnetic signals are not reproduced by the sill-like intrusion. A second preferred model is proposed using gravity data only (Figure 45). Density is in units of g/cm^3 and magnetic susceptibility is in cgs units.

Figure 45: Cross section model along line B-B' modelled using gravity only. The intrusion remains largely unchanged from the previous model in Figure 44, except that the magnetic signal is interpreted to be produced by surrounding rocks, and not the intrusion itself, suggesting that it has low magnetic susceptibilities, and therefore low magnetite content. Note that density is in units of g/cm^3 .

6.3.4 Discussion

The formation of the Lake Victoria Dyke Swarm (LVDS) and coeval inner intrusions is a highly debated topic. There does not appear to be a single model as yet proposed that can explain the formation of the entire c. 1380 Ma Kunene-Kibaran event at the Lake Victoria centre. Several plume and non-plume origins have been proposed for the origin of the LVDS and inner intrusions, such as a proposal for a deep-crustal magma chamber beneath the LVDS (Mäkitie et al., 2014), however the plume origin remains favourable, especially given the voluminous magmatism emplaced over a very short time period.

There are three leading proposals in which the LVDS and coeval intrusions could be linked with a mantle plume, which are summarized in full in Mäkitie et al. (2014). In short, these are: 1) a plume centre at Lake Victoria, with the LVDS representing two failed rift arms, while a third minor branch may be hidden beneath Lake Victoria (Figure 46a), 2) a plume the northern end of the LVDS (Figure 46b), and 3) a plume located at the centre of the LVDS (Figure 46c).

We consider the third scenario, in which a mantle plume is located at the centre of the LVDS, and propose that the elongate gravity anomalies R1 and R2 indicate rifting and, more specifically, triple junction rift arms given their orientation towards the centre of the LVDS. In the case of Lake Victoria, the rift arms and the circumferential swarm would have acted as tensional fractures that would have aided in the distribution of magma throughout the crust, and would have led to the formation of the two (and possibly three) intrusions identified from gravity data. Magma would have been channeled along these fractures towards crustal weak spots marking the intersection of circumferential and radial structures, the latter of which is recognized by gravity data. At these weak

spots in the crust, magma is inferred to have pooled and formed large chambers in the middle to lower crust (Figure 47).

Rifts will be associated with positive gravity anomalies if there is a density contrast between the intrusive rock and the bedrock, which would be acquired from mafic-ultramafic magma being emplaced along the rift. In their more shallow levels, these would typically host rift-related sediments. However, with enough erosion these sediments will be removed. This is not uncommon. A similar interpretation involving cryptic rifts is associated with the Matachewan LIP of the southern Superior craton (Ernst, 2014a), where discrete subswarms of dykes in the Matachewan radiating swarms are thought to represent deeply eroded rifts. So the basement geology to the proposed cryptic rift is not anomalous because we have eroded through any downdropped sedimentary package and so basement rocks are present both in the proposed cryptic rift and outside. A difference with the Matachewan case is that there are dykes that run parallel to each other—but this is not the case at Lake Victoria.

From bedrock geology maps, there is no apparent source for the gravity high along R1 at the surface. We do note that the gravity high along R2 coincides with the Archean Dodoman System to some extent, which extends across the central part of the Tanzania craton (

Figure 39). The Dodoman System is composed of highly metamorphosed and migmatized sediments with minor igneous rocks (Taylor, 2009). Being initially sedimentary in nature, rocks of the Dodoman System are not likely to have high enough densities to produce the gravity signal we observe at R2. Furthermore, although the northwest portion of the Dodoman System roughly correlates with the gravity highs R2 and LV2, to the south the Dodoman System trends northeast while the gravity high continues southeast. This distinction in trend in the south and the nature of

the rocks that form Dodoman System indicate that these rocks and the gravity high at R2 are unrelated.

If the positive gravity lineaments R1 and R2 indeed mark triple junction rift arms, then this would indicate that domal uplift occurred in the centre of present-day Lake Victoria. This is supported by a common link between triple junction rifting, or radiating dyke swarms, and plume-induced uplift (e.g., Ernst et al., 1995). The origin of circumferential swarms is poorly understood, especially at the scale of the LVDS, however circumferential fractures can be produced as a result of central collapse following domal uplift. Furthermore, radial and concentric fracturing are not mutually exclusive for a given event (e.g., Baragar et al., 1996; Ernst and Buchan 1998; Ernst et al. 2001; Montési, 2001; Ernst 2014b; Ernst et al., 2014; Klaussen et al., 2014).

If we consider the central plume model with R1 and R2 representing triple junction rifting, then we have to consider the timing of the emplacement of the LVDS with respect to the rifts and to the emplacement of the outer intrusions. It is not likely that triple junction rifting and the circumferential dyke formed at the same time, as triple junction is linked with the onset of uplift while concentric fracturing is linked with later collapse of the central block. The LVDS would have presumably been emplaced after the domal uplift had decayed, intruding into faults created during central graben collapse. Given that the intrusions LV1, LV2 and perhaps LV3 are all at a common distance from the plume centre and on the outer periphery of the circumferential swarm, then the timing of these intrusions LV1, LV2 and LV3 would be linked with the timing of the circumferential dyke swarm. In this case, the present model would suggest two stages of activity: earlier uplift associated with rifting and later development of the circumferential system and the layered intrusions at this time.

The Kunene-Kibaran LIP is the best candidate from the global database of LIPs that resembles the Mackenzie circumferential intrusions. In both cases, mantle plumes are inferred to have caused regional-scale domal uplift leading to similar stress regimes in the crust. Also, similar to the Mackenzie intrusions, the intrusions at LV1, LV2 and potentially LV3 are located at several hundred kilometers from the plume centre, indicating that the Mackenzie and Lake Victoria events are of similar scale. The most important differences between the Mackenzie and Kunene-Kibaran LIPs are:

- 1) The Mackenzie mafic bodies almost completely circumscribe the plume centre, while the Lake Victoria bodies have only been traced circumscribing the plume centre over a 180° arc, 2) the Mackenzie event led to the formation of a giant radiating dyke swarm, while the Kunene-Kibaran event led to the formation of triple junction rifting, but no radiating swarm has been identified, and 3) a series of coeval intrusions are observed inside the circumferential LVDS (the Kabanga-Musongati lineament), while no inner intrusions are observed at Mackenzie.

In regards to (1), the continuation of the LVDS towards the west is unclear due to the presence of the EARS and because of a lack of data to the west. This will remain unclear until evidence for its continuation is observed; aeromagnetic data in poorly-studied regions to the west will be the key to its recognition. It is possible that the LVDS continues to the west and forms a complete arcuate swarm, along which we would expect a continuation of the mafic-ultramafic intrusions along the outer periphery of the swarm.

Concerning (2), both radiating dyke swarms and triple junction rifting are the product of radial stresses. Both can occur (e.g., at Yakutsk-Vilyui, Siberia) and it is interpreted that the radiating system should be produced first and followed by local breaks along weak points leading to triple

junction rifts. If the crust at Lake Victoria broke quickly into triple junction rifts, then a radiating system would not have had time to develop.

Lastly, concerning (3), it is expected that smaller intrusions (< 1 km to several kilometers wide) will be emplaced directly above the plume centre, where magmatism and temperatures are maximum. A lack of similar intrusions observed at Mackenzie is most likely because the intrusions are small therefore cannot be detected from gravity and magnetic data at the scale used in this study, or because they remain buried.

Figure 46: Three scenarios relating the LVDS with Mantle Plumes from Mäkitie et al., 2014. a) A plume centre beneath Lake Victoria, with the LVDS marking triple junction rift arms, b) a plume centre at the northern edge of the swarm that was curved as a result of a paleostress field and c) a concentric swarm with a plume centre at the middle of the swarm.

Figure 47: Schematic diagram for the formation of three large (80-90 km diameter) mafic-ultramafic intrusions on the outer periphery of the LVDS and Lake Victoria Dyke Swarm (LVDS) and along a possible triple junction rift system (identified from gravity), with a plume centre at the intersection of the triple junction rift arms and at the centre of the LVDS. Note that the western portion of the LVDS is not yet identified, and that in the event of a western continuation of the LVDS, we expect that 3-5 additional intrusions and rift arms will be located on the western edge of the EARS.

6.4 Deccan LIP (66 Ma), Western India

6.4.1 Geological Overview

The 66 Ma Deccan LIP, India (Figure 48 and 49), is one of the largest and best-preserved LIPs on Earth, and has received much attention due to its possible role in the K-T (Cretaceous-Tertiary) boundary mass extinction (e.g., Chatterjee et al., 2013). An estimated 500,000 km² of west-central India is covered by tholeiitic Deccan basalts, with original lava volumes estimated at 1.2×10^6 km³ (e.g., Sen, 2001; Jay et al., 2009). The Deccan volcanic flood basalts erupted onto Archean and Proterozoic shield rocks as well as areas offshore, covering most of the southern Indian Dharwar and central Indian cratons (Devey and Stephens, 1991). The flood basalts are bordered to the east and south largely by Archean granulite terranes intruded by numerous Proterozoic mafic dykes and the Western Ghats Belt, to the north by Neoproterozoic to Phanerozoic cover and the Aravalli craton, and to the west by the Indian continental shelf (Figure 48).

Currently, three main pulses of magmatism are recognized and erupted over three magnetic chrons – C29n and C29r and C30n (Figure 49), (Vandamme et al. 1991; Chenet et al., 2007; Keller et al., 2011a, b). The first pulse at ~ 67.5 - 68.5 Ma during C30n was short and only minor amounts of magma were erupted. These are best represented by the alkaline Sarnu-Dandali volcanics in the Barmer District (Ba) and the Mundwara volcanics in the Sirohi District (Si), both in northern India (Basu et al., 1993), (Figure 48). The main pulse produced most of the Deccan lavas during a short interval of less than 1 million years at 65 – 66 Ma during the C29r magnetic chron, straddling the Cretaceous-Tertiary boundary (Chatterjee and Rudra, 1992; Chenet et al., 2007; Sen and Chandrasekharam, 2011), and was shortly followed by a third smaller pulse at 64.8 Ma (Figure 49).

Four major rift zones traverse the Deccan flood basalts (Figure 48): the north-south Cambay rift, the east-west Kutch (Kachchh) rift, the West Coast rift, and the east-west Narmada-Tapti (Tapi) rift system that extends across central India (Mishra, 1977; Sheth, 2005). Rifting along the Kutch rift occurred in the late Triassic to early Jurassic and rifting along the Cambay rift occurred in the Cretaceous during the eruption of the Deccan basalts (Mishra et al., 2001; Sheth, 2005). The Narmada-Tapti and West Coast rifts are Precambrian suture zones between the northern Aravalli and the southern Dharwar cratons (Naqvi et al., 1974), which acted as prominent lines of weakness that were reactivated during Deccan magmatism (Sheth, 2005). In eastern and central Saurashtra, there are a number of N-S and NNE-SSW geophysical trends that parallel the Cambay rift and which similarly formed during the Late Cretaceous (Mishra et al., 2001). It is interesting to note that these N-S and NNE-SSW trends occur in pairs, which Mishra et al. (2001) interpret as an indication of fracture zones/ faulting. In particular, rifting in the Late Cretaceous led to the formation of the Cambay rift basin (CRB, Figure 48), which represents a failed rift basin (e.g., Bhandari and Choudhary, 1975; Kundu and Wani, 1992; Biswas et al., 1994; Madabhushi et al., 2008; Sahoo and Choudhuri, 2012). The basin was formed in three stages: 1) an early extension and rifting stage during the Cretaceous, 2) a thermal subsidence stage during Paleocene – Early Miocene, and 3) a compression and structural inversion stage during the Middle Miocene and younger (Sahoo and Choudhuri, 2012). Deccan Trap basalts that erupted during the onset of Deccan magmatism form the basement of the Cambay Rift basin (stage 1), which are overlain by continental non-marine sediments of the Olpag Formation that were deposited shortly afterwards (stage 2), (Madabhushi et al., 2008; Sahoo and Choudhuri, 2012).

The origin of the Deccan Volcanic Province is a highly debated topic. Some authors propose that the Deccan basalts are the result of conventional plate tectonic processes (e.g., Chandrasekharam and Parthasarathy 1978; Sheth, 2005), while others propose a bolide impact model for the formation of the Deccan Traps (Chatterjee and Rudra, 1992; Chatterjee et al., 2006; Richards et al. 2015). More commonly, the Deccan flood basalts are attributed to the Indian craton traversing northward over the Réunion plume during the Cretaceous - Early Tertiary (e.g., Morgan, 1981; Mahoney 1988, Richards et al. 1989; Campbell & Griffiths, 1990; Duncan and Richards 1991; Campbell, 1998; Mahoney et al., 2002; Sen and Chandrasekharam, 2011). The subsequent post-Deccan Réunion hot spot trail is represented by the Chagos-Maldives-Laccadive Ridge, the Saya de Malha and Nazareth Bank, Mauritius and the present site in the Indian Ocean where it is currently producing volcanic activity on Réunion Island (Figure 50). The plume model is generally favored as it best accounts for the large volumes of lavas erupted in a short time span (> 80 % of the Deccan lavas were erupted in < 1 million years), the high temperatures in magma generation (estimated at $1,550 \pm 2.5$ °C and 2.5 ± 0.4 GPa), and the track of the Deccan-Laccadives-Maldives-Réunion hotspot (Sen and Chandrasekharam, 2011).

The Réunion plume is generally linked with the breakup of Madagascar from India during the Middle to Late Cretaceous, and the breakup of the Seychelles plateau from India during the late Cretaceous which was shortly followed by the eruption of the Deccan volcanic rocks (Figure 48b, c), (e.g., McKenzie and Sclater, 1971; Raval and Veeraswamy, 2003, 2000; Surya Prakasa Rao and Tewari, 2005). Following the arrival of the Réunion plume at ~ 67 Ma, plate reconstruction models from paleomagnetic data indicate that the Indian subcontinent moved northward and rotated a total of ~ 20° counterclockwise (Figure 50), at rates of 20 cm/year and 1.0°/Myr from the Lake

Cretaceous (~ 67 Ma) to the Early Eocene (~ 50 Ma), at which point it drastically slowed down to 5 cm/year and 0.1°/Myr (McKenzie and Sclater, 1971; Patriat and Achache, 1984; Lee and Lawver, 1995; Copley et al., 2010; Chatterjee et al., 2013). Herein, a plume origin is our preferred model for the formation of the Deccan LIP. Even so, the location of the plume centre remains debatable.

Three plume centres have been postulated. 1) Some propose that the Réunion hotspot was located near Mumbai (Bombay) during eruption of the Deccan lavas (white star, Figure 48), where a large geophysical anomaly is apparent on the west coast of India (e.g., White and McKenzie, 1989). 2) Others propose a plume centre at the intersection of the Narmada-Tapti, Cambay and West Coast rifts (red star, Figure 48), (e.g., Burke and Dewey, 1973; Courtillot et al., 1999; Ernst and Buchan, 1997), which some have proposed represents a triple junction rift system. 3) A third plume centre location is to the north of Cambay where the Réunion hot spot is inferred to have first arrived at the base of the lithosphere (Kennett and Widiyantoro, 1999) (blue star, Figure 48).

Generally, the preferred location is at 2 (red star), at the intersection of the Narmada-Tapti, Cambay and West coast rifts. Some of the strongest evidence in support of this plume centre is the geometry of dyke swarms throughout the Indian craton (Figure 49a), (Ju et al., 2013). The high concentration of parallel dykes within the Narmada-Tapti and West Coast rifts is supportive of a large magma chamber at their intersection, which they interpret as marking the location of the plume centre. The fact that these rifts represent ancient lines of weakness in the crust (Naqvi et al., 1974; Sheth, 2005) means that their intersection would indeed represent a particularly weak spot in the crust that existed prior to the arrival of a mantle plume where magma would likely have been concentrated, but could also represent the locus of magma channeling from a plume centre that was located nearby. Given the numerous pre-existing zones of weakness throughout the Indian craton,

the largest concentrations of volcanism might not be directly above the plume centre, as magma could have been channeled towards these zones of weakness. If so, it is unlikely that these rifts indicate triple junction rifting resulting from plume-generated domal uplift.

The third postulated plume location to the north of Cambay can be similarly interpreted to be located at the intersection of a triple junction rift system, but instead it is at the intersection of the Cambay and Kutch rift. Contrary to the ancient lines of weakness within the Narmada-Tapti and West coast rifts, these were formed at a similar time as the arrival of the Deccan plume in the Cretaceous. This plume location is also at the focus of rifts located along the western and eastern edges of the Cambay rift basin (see discussion below). Aside from its relation with rift structures in north-west India, supporting evidence towards a northern plume location is indicated by seismic tomography imaging that shows a distinct seismic anomaly at the northern edge of the Cambay rift basin (Kennett and Widiyantoro, 1999) that could be the expression of a fossil plume head at the inferred location of the arrival of the Réunion plume head. This plume centre location and supporting evidence are further detailed in the following sections.

Figure 48: Geology and tectonic map of the Indian Shield and the Deccan Traps, at a) present, b) 65 Ma, and c) 88 Ma. Postulated locations of the Deccan plume centre are identified by stars (see text for detail). Ba, Barmer District; Ch, Chattisgarh Basin; CIS, Central Indian Shear Zone; CRB, Cambay Rift Basin; GR, Godavari Rift; M, Madras Block; Mk, Malanjhand; MR, Mahanadi Rift; N, Nilgiri Block; NS, Narmada-Son Fault Zone; PC, Palhjat-Cauvery Shear Zone; R, Rengali Province and Kerajana Shear Zone; S, Singhbhum Shear Zone; Sa, Sirohi District; V, Vindhyan Basin. Modified from French et al. (2008) and Sheth, 2005, after Norton and Sclater (1979) and Mahoney (1988).

Figure 49: a) General map of the eastern Deccan LIP (Ju et al., 2013). b) Age distribution of the three main pulses over three chrons (Keller et al., 2011a, b). c) List of formations observed at locations 1 through 17 corresponding to figure d (Widdowson et al., 2000). d) Age distribution of the Deccan stratigraphy (Jay and Widdowson, 2008) and average directions of magnetization reported for Deccan (Vandamme et al. 1991). Star – proposed plume centres. Figure modified from Ernst (2014a).

Figure 50: Deccan–Réunion hot spot trail on the west side of the Indian plate (red line) and the Rajmahal–Kerguelen trail on the east side of the Indian plate (blue line) with ages at select locations (in units of Ma). Deccan traps are shown in red, and the offshore Somnath volcanic platform that erupted 500 Myr prior to the Deccan traps are shown in green. Abbreviations: CIDG, Central Indian Deformation Zone; CIR, Central Indian Ridge; CR, Carlsberg Ridge; SEIR, South East Indian Ridge; and SWIR, Southwest Indian Ridge. From Chatterjee et al. (2013).

6.4.2 Geophysics in the Deccan Plume Centre Region

Expansive geophysical studies have been conducted across the Indian continent, including gravity, magnetic and seismic surveys. These, combined with drilling and field investigations have greatly contributed to an understanding of some of the buried components of the Deccan LIP. In general, the central and eastern components of the Deccan LIP have been the most extensively studied, but the LIP as a whole, including the western portion, is one of the most extensively studied LIPs on Earth. Of primary interest to this study, gravity data have been widely applied to the identification of mafic and ultramafic intrusions throughout the Deccan Traps. A large number of these have been modelled, and a summary of these studies is provided herein, as well as a summary of three gravity anomalies in western Saurashtra that have not been modelled previously.

From gravity surveys, a number of shallow intrusive complexes (9+) linked to Deccan volcanism have been identified along the west coast of India and within the Narmada-Tapti rift system (Bhattacharji et al., 2004). The largest and perhaps the best known of the Deccan-related intrusions is situated along the western continental margin. Here, a + 70 mgal gravity anomaly at Mumbai (Bombay) extends north-south along the coast, and is aligned with + 30 mgal gravity that continue northward along the coast (Figure 51). Bhattacharji et al. (2004) model these anomalies as a single 300 km long, 30 km wide and 12 km thick elongated and roughly ellipsoidal high-density body that lies at a depth of 6 km. In the same study, eight + 10 mgal to + 30 mgal gravity anomalies along the Narmada-Tapti rift were modelled using gravity data and are modelled at similar depths of 6 to 8 km depths. Their findings are summarized in Table 8.

Chandrasekhar et al. (2002) conducted a similar study of gravity anomalies in the western exposure of Deccan flood basalts, and incorporate both gravity and magnetic data into their

modelling. Here, six + 40 to + 60 mgal circular gravity highs occur in the west-central and eastern Saurashtra peninsula (Figure 52), (Mishra et al., 2001). The gravity anomalies to the west coincide with exposed and well-known volcanic plugs, which are referred to by multiple names. These are the Girnar (Junagadh), the Barda (Porbander) and the Alech plugs (Figure 52, A-C; Figure 53, 1-3). It has been suggested by some (e.g., Karanth and Sant, 1995; Mishra et al., 2001) that the gravity anomalies D1, D2 and D3 (Figure 55) coincide with minor exposures of alkaline and acidic intrusions, but it remains unclear to what extent these are exposed and whether these exposures are a part of the same intrusive bodies that produce the large gravity anomalies, or if they are minor intrusions sourced from deeper units. Remanent magnetization within the Deccan Traps is predominant, and is apparent from magnetic high/low pairs at locations A-F from magnetic anomaly maps across Saurashtra (± 1 nT), particularly at Junagadh, where the magnetic high to the south is considerably larger than what would be expected for an entirely induced magnetic component in a region with an inclination value of 30° (Figure 54), (Chandrasekhar et al., 2002).

Modelling across two of the intrusions (the Junagadh and Barda volcanic plugs; A and B in Figure 52) suggests bulk densities of 2.9 and 2.88 g/cm³, respectively, and magnetic susceptibility values of 2.5×10^{-3} cgs (3.14×10^{-2} SI). Contrary to direct measurements of samples from exposed rocks suggesting a reversed polarity, the models by Chandrasekhar et al. (2002) indicate normal polarity. This suggests that the bulk composition of these intrusions is different from the exposed sections. They also suggest that the bulk densities are greater than those that are observed at the surface, which may indicate a lower ultramafic zone at the base of the intrusion or high-density magmatic underplate. Their results are summarized in Table 9.

To date, modelling in previous studies has not been done across the three circular gravity highs that are linearly aligned along the western edge of the Cambay rift basin in Saurashtra (D1, D2 and D3; Figure 55). These are qualitatively attributed to volcanic plugs resembling those at Junagadh and Barda (Mishra et al., 2001; Chandrasekhar et al. 2002), but have otherwise only been alluded to. The present study contributes geophysical models of these three anomalies using gravity and magnetic data to provide a quantitative interpretation of the intrusions.

The data used in the present study are assembled from airborne surveys and have been upward continued to 4 km to be compiled into EMAG2, and are therefore not able to resolve the high/low magnetic pairs resolved in the magnetic data presented by Mishra et al. (2001) and Chandrasekhar et al. (2002). Consequently, the relation between the magnetic anomalies and the gravity anomalies at D1, D2 and D3 are not as well correlated from the data used herein (see Figure 56 for pole-reduced magnetic data in eastern Saurashtra from EMAG2). Nevertheless, we have confidence in the usefulness of the data for modelling, where the response of the model is upward continued in Oasis Montaj to be directly compared with observed magnetic data, and is highly sensitive to variations in the model.

In addition to gravity and magnetic surveys, seismic studies throughout India have also had a major role in imaging the subsurface. In particular, these studies indicate that magmatic underplating in the lower crust is widespread under the Deccan Traps (e.g., Surya Prakasa Rao and Tewari, 2005). Additionally, seismic tomography studies of India have revealed a potential location for the Deccan fossil plume head (Kennett and Widiyantoro, 1999), which show a 200 km wide, cylindrical region of low seismic velocity in the upper mantle directly to the north of the gulf of Cambay (Figure 57). The centre of this anomaly lies directly beneath the 68.5 Ma Sarnu-Dandali and

Mundwara volcanic sequence and extends southward almost as far as Cambay (Ba and Si, Figure 48). This, in addition to its association with the oldest components of the Deccan LIP is a strong indication that the anomaly represents the remains of the initial plume head, which would have had to have been carried with India over the past 65 Ma (Kennett and Widiyantoro, 1999).

Figure 51: Bouguer anomaly map of the Deccan traps. Profile lines A-B, C-D intersect the Bombay anomaly and its continuation towards the north. Profile lines Th-Si, Uj-Ma, Kh-Pu and Hi-Mn were selected along Deep Seismic Sounding (DSS) lines from Kaila (1988) that intersect the Narmada-Tapti rift. From Bhattacharji et al. (2004).

Table 8. Dimension, depth and estimates from gravity data modelling of Deccan-related mafic bodies along the western continental margin rift and along four DSS (Deep Seismic Sounding) profiles (Kaila et al., 1987; Kaila, 1988) intersection the Narmada-Tapti rift. Bhattacharji et al. (2004). ρ – density.

Location	Width top (km)	Width base (km)	Length top (km)	Thickness (km)	Depth (km)	ρ (g/cm ³)
Mafic body along the west coast rift						
Bombay/Mumbai	25.0	40.0	300.0	12.0	6.0	2.90
						2.97
Mafic bodies on the northern side of the DSS profiles						
Hirapur-Mandla	6.5	13.0	20.0	9.0	6.0	2.97
Khajuria Kalan- Pulgaon	6.0	9.0	26.0	13.0	6.0	2.97
Ujjain-Mahan	10.0	10.0	18.0	13.0	8.0	2.97
Thuadara-Sindad	26.0	26.0	23.0	8.0	6.0	2.90
Mafic bodies on the southern side of the DSS profiles						
Hirapur-Mandla	6.5	23.0	26.0	15.0	6.0	2.97
Khajuria Kalan- Pulgaon	10.0	38.0	25.0	14.0	6.0	2.97
Ujjain-Mahan	20.0	20.0	28.0	15.0	8.0	2.97
Thuadara-Sindad	15.0	15.0	14.0	12.0	6.0	2.97

Figure 52: Bouguer anomaly map of the western-most portion of the Deccan flood basalts, in Saurashtra, west India, with profile lines X-X' and Y-Y' from Chandrasekhar et al. (2002). They provide physical property estimates of two circular gravity anomalies (A and B) and one magnetic anomaly (C) near Junagadh and Porbander. Modelling results are summarized in Table 9 (note that the gravity anomaly at B and the magnetic anomaly at C are considered as one body in Table 11). Gravity highs D, E and F near Rajula, Palitana and Vallabhipur are qualitatively inferred to represent similar-type intrusions, but no modelling was done across these units. Figure from Chandrasekhar et al. (2002).

Figure 53: Geological map of the western Deccan LIP in Saurashtra, India. Volcanic plugs are: 1- Girnar/Junagadh, 2- Barda, 3- Alech, 4- Chogat, and 5- Chamardi. Figure from Surya Prakasa Rao and Tewari (2005).

Figure 54: Magnetic anomaly map of western Saurashtra showing magnetic highs and lows that coincide with the gravity anomalies at A-F, and average remanent magnetization (inset) reported for the Deccan traps (Vandamme et al., 1991). Figure from Chandrasekhar et al. (2002), after Mishra et al. (2001).

Table 9. *Depth, dimensions, density, and magnetic property estimates from joint modelling of gravity and magnetic data (Chandrasekhar, 2002) in the west-most portion of Deccan flood basalts, near Saurashtra. ρ – density, k- magnetic susceptibility, RM- Natural remanent magnetization, D- declination, I- Inclination.*

Location	Width top (km)	Width base (km)	Thickness (km)	Depth (km)	ρ (g/cm ³)	k (SI)	RM (A/m)	D	I
Mafic bodies in western Saurashtra									
Junagadh	14	16.0	17.0	1.0	2.9	0.031	0.7	340°	-50°
Porbander	18.0	24	17.5	0.0	2.88	0.031	0.8	337°	-38°

Figure 55: Bouguer anomaly map of the western component of the Deccan LIP, India. Contour lines are drawn at 10 mgal intervals. D1, D2 and D3 indicate anomalies modelled in the present study, located in Eastern Saurashtra, India. Stars indicate potential plume centre locations.

Figure 56: Magnetic anomaly map reduced to the pole. D1, D2 and D3 indicate the location of the three anomalies identified from gravity data shown in Figure 55.

Figure 57: Map view of P-wave velocities at 80 km depth from seismic tomography studies, superimposed on plate boundaries (thick black lines). Blue colors indicate a region of lowered seismic velocities in the upper mantle directly to the north of the Cambay rift basin, and is interpreted as a fossil plume head. Figure modified from Kennett and Widiyantoro, 1999.

6.4.3 Modelling

Despite the complexities involved in modelling intrusions with substantial remanent magnetization components, especially when paleomagnetic studies have not been done on these rocks, and the lack of knowledge pertaining to the extent and nature of the exposed alkaline rocks (i.e. whether these alkaline exposures represent the main intrusive body or some form of offshoot from the main body), three models along line A-A' (Figure 55 and 56) intersecting the +70, +50 and +67 mgal gravity anomalies are presented here.

The first model (model 1) assumes that the intrusions extend to the surface and are partially exposed. The second model (model 2) assumes that the intrusions are deeper in the crust (upper to middle) and exist as three distinct bodies that are fed by feeder dykes or sills which are not resolved at the present resolution. Lastly, the third model (model 3) assumes that the intrusions are located in the upper to middle crust, but are joined at the base, indicating a strong component of magmatic underplating.

Included in all models are crustal information from CRUST1.0 and crustal information from geophysical studies and drilling near D1, D2 and D3 within the Cambay rift, which indicate that the Deccan basalts have a typical thickness of 4 km in this region (Ramanathan 1981; Sheth et al., 2013). Studies also indicate a thinned crust along the rift (32-33 km), (Surya Prakasa Rao and Tewari, 2005). From paleomagnetic studies (Vandamme et al. 1991), Deccan volcanic and intrusive rocks in the vicinity of the anomalies D1-D3 have reported remanent magnetization of both normal and reversed polarities. As mentioned previously, the Junagadh and Porbander plugs to the west have normal polarities with remanent magnetization values of $D = 340$ and $I = -50$, and $D = 337$ and $I = -38$, respectively (Figure 52, Table 9), and the values proposed by Chandrasekhar et al. (2002) for D1-D3,

based on magnetic field observations, are of normal polarity with suggested values of $D = 337^\circ$, $I = -38^\circ$, and $D = 340^\circ$, $I = -50^\circ$. Note that both normal and reversed polarities are considered in the present models.

Model 1, which assumes that the intrusive bodies are exposed at the surface, is shown in Figure 58. The model places three separate mafic intrusions in the upper crust (density of 2.9 g/cm^3), which are underlain by underplated magma in the lower crust with a similar mafic composition (density of 3.0 g/cm^3), which is supported by seismic data that indicates underplating in the lower crust (Surya Prakasa Rao and Tewari, 2005). The major limitation with this model is the difficulty in reproducing the magnetic signal with intrusive bodies that extend to the surface (Figure 58, upper panel). The response of the model does not reproduce the observed magnetic data with the best estimates of magnetic susceptibility and remanent magnetization.

A second model is proposed that assumes a deeper source for the gravity anomalies (Figure 59). In this model, single intrusions are located in the upper-middle crust at depths of 8.0 to 8.5 km. The intrusions are mafic in composition (with densities of $3.0 - 3.14 \text{ g/cm}^3$) and have moderate magnetic susceptibility values ($0.002 - 0.005 \text{ cgs}$, or $0.025 - 0.063 \text{ SI}$) with a reversed remanent magnetization component (0.001 emu/cm^3 , or 1 A/m). Deeper intrusive bodies reproduce the observed magnetic signal better than intrusions that extend up to the surface, and better reproduce the long-wavelength trend in the data, but the model still fails to reproduce the entire signal. Therefore a third model is proposed.

The third model assumes similar sources as in model 2, but includes an underplate component in the lower crust (Figure 60). The intrusions are mafic in composition with densities of $2.9 - 3.1 \text{ g/cm}^3$ and are located at 8 to 10 km depths beneath the surface. The observed magnetic

field is reproduced by intrusions with normal polarities, with $D = 135^\circ$, $I = -50^\circ$. The mafic intrusions have moderate magnetic susceptibilities, with values ranging from 0.0001 – 0.004 cgs (0.001 – 0.05 SI), and a remanence component of 0.002 – 0.01 emu/cm³ (2 – 10 A/m). Similar values are inferred for the underplate component ($S = 0.003$ cgs or 0.038 SI, and $M = 0.006$ emu/cm³ or 6 A/m), but the magnetic signal is best reproduced for an underplate with a reversed polarity.

The third model (Figure 60) best reproduces the observed gravity and magnetic anomaly data, while remaining consistent with previous studies. In particular, this model remains consistent with geophysical, petrological and geochemical models that estimate that the Deccan lavas evolved in multiple magma chambers at depths of 6 to 8 km (Sen, 1995; Bhattacharji et al., 1996; Bhattacharji et al., 2004; Ju et al., 2013). Therefore, model 3 is the preferred model for the gravity anomalies at D1, D2 and D3.

Figure 58: Profile model 1 along line A-A' (Figure 55 and 56). Density (D) is in units of g/cm^3 , magnetic susceptibility (S) is in cgs units and remanent magnetization (M) is in units of emu/cm^3 . MI and MD are magnetic inclination and declination, respectively.

Figure 59: Profile model 2 along line A-A' (Figure 55 and 56). Density (D) is in units of g/cm^3 , magnetic susceptibility (S) is in cgs units and remanent magnetization (M) is in units of emu/cm^3 . MI and MD are magnetic inclination and declination, respectively.

Figure 60: Profile model 3 along line A-A' (Figure 55 and 56). Density (D) is in units of g/cm^3 , magnetic susceptibility (S) is in cgs units and remanent magnetization (M) is in units of emu/cm^3 . MI and MD are magnetic inclination and declination, respectively.

Table 10: Depth, dimensions, density, and magnetic property estimates from joint modelling of gravity and magnetic data along profile line A-A' (Figure 55 and 56) in eastern Saurashtra. ρ – density, k - magnetic susceptibility, RM- remanent magnetization, D - magnetic declination, I - magnetic inclination.- this study (model 3).

Location	Width top (km)	Thickness (km)	Depth (km)	ρ (g/cm ³)	k (SI)	RM (A/m)	D	I
Mafic bodies in eastern Saurashtra								
D1-Rajula (A')	45	13	9.6	3.0	0.025	1	335°	-50°
D2-Politana	60	12	8.7	2.9	0.001	1	335°	-50°
D3-Vallabipur (A)	60	13	7.9	3.1	0.050	2	335°	-50°

6.4.4 Discussion

The normal polarities modelled at D1, D2 and D3 ($D = 335^\circ$, $I = -50^\circ$) indicate that these intrusions were either emplaced during the first stage of magmatism at > 65.6 Ma or during the final stage at < 64.8 Ma, respectively (Figure 49). Given that these intrusions were emplaced adjacent to similar yet exposed intrusions that are dated and belong to the earliest phase of Deccan magmatism at ~ 68.5 Ma, then it is reasonable to consider these intrusions as early components of the Deccan LIP and, more specifically, that these intrusions were emplaced during the first eruptive phase of Deccan magmatism during the C30n magnetic chron.

In terms of their distribution relative to the plume centre, these intrusions are particularly intriguing because of their linear alignment along the western edge of Gulf of Cambay and their relation with similar intrusions along the eastern edge of the Gulf (Bhattacharji et al., 2004). Although no magnetic modelling has been done for the eastern set of intrusions, their similar alignment and positioning along the Gulf of Cambay suggests a relation with the intrusions at D1, D2 and D3. Thus, we consider these intrusions (D5, D6 and D7) as potentially belonging to the first stage of Deccan magmatism.

These two sets of linearly-aligned intrusions are emplaced along rifts that are oriented towards the northernmost postulated plume centre (Figure 61), that also coincide with the seismic anomaly indicating the location of the fossil plume head. Provided that the plume centre was to the north during their emplacement, then these intrusions represent a distinct distribution of mafic (and possibly ultramafic) intrusions in the plume centre region; mainly these are an excellent example of intrusions linearly aligned along rifts, and which are potentially oriented towards a plume centre.

Although the northern plume location (blue star, Figure 48) is not generally considered as the plume centre for the main eruptive phase, seismic data and outcrops of early-Deccan Traps points towards a plume location to the north of Cambay during the initiation of the Deccan eruption. Furthermore, paleomagnetic studies indicate that the plume would have been located here at the onset of Deccan magmatism (Figure 50). It is therefore feasible that this location marks the plume centre for the first pulse at least, which includes the emplacement of the intrusions along the Cambay rift basin.

The location of the plume during the second and third pulses remains uncertain. One scenario is that the plume head was dragged along with the Indian craton during the span of Deccan magmatism. If this occurred, then this would mark the location for the plume centre for the entire event. Such an occurrence is not typical for plumes, but a plume being carried with the lithosphere is not unheard of (Olson, 1990). For example, a similar event occurred with the Paraná flood basalts, where a similar 200 km wide low velocity zone extending to depths of 200 km is interpreted to mark the location of a fossil plume stem that was carried with the South American continent since the eruption of the plume at 130 Ma (VanDecar et al., 1995; Kennett and Widiyantoro, 1999)

Alternatively, the plume centres at the intersection of the Narmada-Tapti, Cambay and West Coast intersections (red star, Figure 48), and at Mumbai (white star, Figure 48) may represent plume centres during the second and third Deccan pulses, respectively. Typically, continents move slowly enough that a single plume centre can be inferred for the entire event, however the Indian craton moved fast enough that if the plume did not attach itself to the base of the Indian craton, then at speeds of 20 cm/year, the Indian subcontinent would have moved approximately 700 km relative to the plume over the span of Deccan magmatism. The distance between the northernmost and

southernmost postulated plume centres is approximately 500 km (Figure 48), so this scenario is entirely plausible.

In summary, in consideration of the location of the intrusions along the Gulf of Cambay, their normal polarities belong to the first-stage of Deccan magmatism. With the understanding that the Reunion hot spot track moved from the north of the Cambay rift at c. 68.5 Ma to the south, reaching the southern tip of India at c. 55 - 60 Ma, we propose that the intrusions along the Cambay rift were formed at the onset of Deccan magmatism, and that these intrusions were emplaced along rifts that converge towards this plume centre location (blue star in Figure 48).

Figure 61: Possible location for the Deccan plume centre (blue star) during the onset of Deccan magmatism at the intersection of the Cambay and Kutch rifts. Dashed red lines locate rifts along the edges of the Cambay rift basin (CRB) where Deccan-related intrusions were emplaced during the first stage of Deccan magmatism.

6.5 High Arctic LIP (130 to 80 Ma), Arctic Canada

6.5.1 Geological Overview

The High Arctic Large Igneous Province (HALIP) is a major magmatic event covering more than 1 million km² of the High Arctic (e.g., Maher, 2001; Drachev and Saunders, 2006; Buchan and Ernst, 2006; Døssing et al., 2013; Ernst, 2014a; Kingsbury et al. 2015). The HALIP is composed of (ferro)gabbroic dykes and sills, and (ferro)basaltic volcanic rocks distributed over Svalbard, Franz Joseph Land, Greenland and the Canadian High Arctic Islands (Jowitt et al., 2014), with the majority of magmatism occurring within the Sverdrup basin on Ellesmere and Axel Heiberg Islands, northern Canada (Figure 62). One of the most prominent features of the HALIP is the Queen Elizabeth radiating dyke swarm and the N-S -trending Lightfoot River dykes subswarm (Embry and Osadetz, 1988; Ernst and Buchan, 1997; Buchan and Ernst, 2006, 2011, 2013), occurring largely within the Sverdrup Basin (Figure 62). The HALIP plume centre is located at the focus of the Queen Elizabeth dyke swarm, directly to the west of Ellesmere Island (Buchan and Ernst, 2006).

The HALIP is composed of four pulses pulses that include three early tholeiitic to weakly alkaline pulses at 130 to 80 Ma and a late alkaline phase at 85 to 60 Ma. The late alkaline pulse may not belong to the LIP strictly speaking, but to a younger unrelated rifting event and is not discussed further here (Embry and Osadetz, 1988; Embry, 2011; Corfu et al., 2013; Estrada and Henjes-Kunst, 2013; Jowitt et al., 2014). The early tholeiitic pulses included the emplacement of sills and dykes within the Sverdrup basin and the formation of flood basalts within the Isachsen Formation and the weakly alkaline pulses included the emplacement of the Wootton intrusion in northern Ellesmere Island and volcanism in the Strand Fiord Formation (e.g. Jowitt et al., 2014). The HALIP remains relatively underexplored due to hostile weather conditions, despite the large scale of the event and

resource potential. However, a recent study by Jowitt et al. (2014) investigated the Ni-Cu and Platinum-Group Element (PGE) prospectivity of the HALIP and suggests that the tholeiitic component of the Canadian HALIP is highly prospective for Ni-Cu-PGEs. They further suggest that mafic-ultramafic sequences within HALIP, especially those associated with the tholeiitic component, should be further investigated as they may provide targets for mineral exploration.

HALIP units are present in the Sverdrup basin, which makes up a large component of Ellesmere and Axel Heiberg Islands, including the Wootton layered intrusion (W) on the northern edge of Ellesmere Island (Figure 62) (Trettin and Parrish, 1987; Estrada and Henjes-Kunst, 2013). The Sverdrup basin is made up of a 15 km thick sedimentary succession and overlies the deformed Franklinian geosyncline (e.g., Forsyth et al., 1979). A long history of crustal instability is apparent in the Sverdrup basin, where a number of northwest trending faults, aligned evaporate domes and linear magnetic anomalies are observed. Uplift had a major effect on the region and exposed a 4 to 6 km thick sedimentary succession of Middle and Late Proterozoic age that trends northwesterly and indicates rifting at about 1.2 to 1.3 Ga. Sedimentary and metamorphic rocks tend to be folded and have a primarily northwesterly orientation (Figure 63) (Balkwill and Fox, 1982).

A small region on the western edge of Ellesmere Island is investigated, marked by a black box in Figure 63 and 64, where a large magnetic anomaly near the inferred plume centre indicates the presence of a buried intrusion linked with HALIP magmatism. The study area is largely covered by sedimentary rock of varying ages and includes rocks with northwesterly trends similar to the general trends of the larger region. It also hosts components of the uplifted Proterozoic rocks and volcanic and plutonic rocks that have been exposed at the surface and which are coeval with the HALIP event. The purpose of this study is to estimate the dimensions of the intrusion and determine if the

geophysical signature observed is compatible with a mafic-ultramafic composition. We also consider its relation to HALIP magmatism, especially given that it is the only anomaly of its type in the plume centre region.

Figure 62: Generalized map of the High Arctic Large Igneous Province (red), with the majority of magmatism occurring within the Sverdrup basin (black dashed line). The Queen Elizabeth radiating dyke swarm and its N-S –trending Lightfoot River dykes subswarm are indicated by red lines. The HALIP plume centre (star) is at the focus of the Queen Elizabeth radiating dyke swarm (Buchan and Ernst, 2006). W – Wooton intrusion. After Jowitt et al. (2014).

Figure 63: Bedrock geology map of Ellesmere and Axel Heiberg Islands showing the northeasterly rock trends resulting from deformational processes. The black box outlines the region of interest to this study, which is situated on the western edge of Ellesmere Island, Nunavut. HALIP-aged volcanic and plutonic rocks are exposed in the study area and are inferred to be linked with HALIP magmatism. Figure from Hadlari et al. (2014).

Figure 64: Simplified geological map of Ellesmere and Axel Heiberg Islands highlighting the HALIP plume centre (star), the coeval dyke swarms (pink) and the coeval volcanic and plutonic rocks in the study area. Black 150 nT contour lines outline a + 850 nT magnetic anomaly on the northwestern coast of Ellesmere Island. Map modified from Garrity and Soller (2009).

6.5.2 Geophysics and Modelling

The + 850 nT magnetic anomaly (Figure 64 and 65) is situated on the western edge of Ellesmere Island, at about 100 km from the HALIP plume centre. The magnetic anomaly is subcircular with a diameter of approximately 40 km, and coincides with a + 70 mgal gravity anomaly. Several gravity anomalies occur nearby that are oriented NW-SE and reflect the general deformational trends of the region. Although similar trends are observed in the gravity data coincident with the magnetic anomaly, the gravity anomaly at this location is larger and has greater amplitude than the typical NW-SE trending gravity anomalies in the region, indicating that multiple sources may produce the gravity signal here. In particular, a deeper body produces the long-wavelength signal of similar scale as the magnetic anomaly, and shallower features produce the short wavelength anomalies.

From bedrock geology maps (Figure 64), it is evident that the causative body for the long-wavelength components of both the gravity and magnetic data does not appear at the surface. Nearby HALIP-aged intrusive and volcanic rocks may be the source for the short-wavelength peaks in the gravity data and may be related to the main body deeper in the crust.

The magnetic anomaly is unique in the area and, given its size, shape and positioning near the HALIP plume centre, it was tentatively interpreted by Buchan and Ernst (2011) to be the expression of a layered mafic-ultramafic intrusion linked with HALIP magmatism (Jowitt et al., 2014). In order to better characterize the intrusion, modelling is conducted across profile line A-A' (Figure 64 and 65) that intersects the anomaly in an east-west direction.

Figure 65: a) Magnetic anomaly and (b) gravity anomaly maps of the HALIP anomaly, located at about 80 km S-E of the HALIP plume centre (star), focused on the subcircular + 850 nT magnetic anomaly on the northwestern coast of Ellesmere Island, Nunavut, with a diameter of about 40 km, and its coincident +70 mgal gravity anomaly. Thin black lines outline the magnetic anomaly on both maps.

Modelling indicates that gravity and magnetic data are well reproduced by a 5 km thick sill-like intrusion with a lateral extent of about 25 km. The model places the intrusion at a depth of 7 km in the upper crust and extends down to a depth of about 10 km (Figure 67). The intrusion is interpreted as being layered with gabbroic to ferrogabbroic components to account for the strong magnetic anomaly. Alternatively, the rock may contain serpentinized ultramafics that would account for the large magnetic anomaly.

Samples collected on Ellesmere and Axel-Heiberg islands (e.g., Jowitt et al., 2014) report that HALIP-aged rocks in the vicinity tend to be basaltic to ferrobaltic in composition. The short wavelength signals in the gravity data (middle panel, Figure 67) occur directly above exposed HALIP-aged volcanic and plutonic rocks and are therefore inferred to be caused by these rock units. In this model, the basalts observed at the surface are not interpreted to extend under sediment cover to the east, however this may be a potential source of variation between the observed and modelled gravity profiles in this area

Figure 66: Profile line A-A' (shown in Figure 65) intersecting the HALIP magnetic anomaly in an E-W direction on the western edge of Ellesmere Island, Nunavut. Black dots are observed magnetic (top) and gravity (middle) data. Solid black lines are calculated responses of the model (bottom). Units of density (D) and magnetic susceptibility (S) are g/cm^3 and cgs ($1 \text{ cgs} = 4\pi \text{ SI}$). Crustal layer depths and densities are from CRUST1.0 (Laske et al., 2013).

A second model (Figure 67) is presented that, although is also modelled with an attempt to best reproduce gravity and magnetic data, is somewhat more schematic. For instance, we infer that the near-surface HALIP-aged rocks were most probably fed from the deeper body through a feeder dyke. We similarly include a feeder at the base of the HALIP intrusion. The main effect of these additions is that the main body in the model is slightly thinner than in the previous model and the density and magnetic susceptibility values vary slightly, however the general shape of the intrusion remains similar in both models.

Figure 67: Profile line A-A' (shown in Figure 65) showing our interpretation of the link between the large body at depth and the near-surface intrusions and include a potential magma source at the base of the large body. Black dots represent observed magnetic (top) and gravity (middle) data. Solid black lines represent the calculated response of the model (bottom). Units of density (D) and magnetic susceptibility (S) are g/cm^3 and cgs , respectively. For conversion to SI units: $1(\text{cgs}) = 4\pi(\text{SI})$. Crustal layer depths and densities are from CRUST1.0, a 1-degree global model of the Earth's crust (Laske et al., 2013). The long wavelength signals (~ 100 km) are reproduced by the sill-like layered intrusion modelled at an average depth of 10 km with a lateral extent of nearly 30 km.

6.5.3 Discussion

The mechanism behind HALIP magmatism is uncertain. Some authors propose rift-related magmatism for portions of the HALIP event, in particular the alkaline components (e.g., Tegner et al., 2011), while others propose plume-related magmatism (e.g., Buchan and Ernst, 2006; Døssing et al., 2013). The focus of the Queen Elizabeth radiating dyke swarm marks a potential mantle plume location that could have supplied magma to the entire HALIP (Buchan and Ernst, 2006). Given the proximity of the magnetic anomaly to the plume centre, the occurrence of HALIP-aged rocks exposed above the anomalous body, and the large size and amplitude of the anomaly indicating it was formed during a major magmatic event, we propose that the mafic-ultramafic intrusion was emplaced as a result of the arrival of the HALIP mantle plume and forms a component of the HALIP plumbing system.

The HALIP magnetic anomaly is unique in the region near the HALIP plume centre as no other anomalies appear to be similar to it, especially none that have the same magnetic anomaly amplitudes and circular shapes. Three reasons are proposed to explain the existence of a single magnetic anomaly. 1) Magma originating from the HALIP plume centre may have been magnetic in nature, but was channeled to one area, where a weak point in the crust likely pre-existed, forming only one major magnetic intrusion near the plume centre instead of multiple intrusions as is observed within other LIPs. 2) Given that this intrusion was identified from magnetic data (as opposed to all other intrusions investigated in this study that were most apparent from gravity anomaly data), this suggests that there is only a small contrast between the body's density with respect the host rock, particularly in comparison with the contrast in magnetic susceptibility. It is possible that additional bodies were intruded near the HALIP plume centre, but are not as magnetic

as the HALIP intrusion and are therefore not obviously apparent using gravity and magnetic methods. Also, the HALIP intrusion may not have been highly magnetic initially, but may contain serpentinized ultramafics that would make it more easily detectable using magnetic methods. 3) Lastly, the geophysical signature of nearby intrusions may simply be obscured by large magnetic anomalies to the north and northwest of the HALIP. These large anomalies to the north are not obviously related to the HALIP and may simply obscure HALIP intrusive components, or may themselves be components of the HALIP plumbing system that we do not yet recognize.

The third scenario is the most probable, particularly given the large and high-amplitude magnetic anomalies that occur throughout the region. For instance, there is the Wootton intrusion to the north that is linked with HALIP magmatism, but any signal from this intrusion is obscured by a large magnetic anomaly (> 200 km) that occurs near northern Ellesmere Island. From limited field observations, it is reported that the intrusion is mainly gabbroic with granite and hybrid rocks, whose density is similar to the country rock density (Jowitt et al., 2014), which may explain why it does not stand out on gravity maps either. The Wootton intrusion was emplaced along a major fault at 92.0 ± 1.0 Ma (U/Pb on zircon; Trettin and Parrish, 1987). The age of the intrusion indicates that it was emplaced during the second stage of magmatism (98-92 Ma) at 92.0 ± 1.0 Ma (e.g. Jowitt et al., 2014). Thus, the intrusions along western and northern Ellesmere Island appear to be distinct in their emplacement. While the Wootton intrusion was emplaced during the second stage of HALIP magmatism, the intrusion on western Ellesmere Island was likely emplaced during the first stage (129-127 Ma) (e.g. Corfu et al. 2013; Jowitt et al., 2014; Kingsbury et al., 2015), given that it is overlain by volcanic and plutonic rocks that were emplaced during the first stage and which were likely sourced from the deeper body.

It is easiest for intrusions to ascend along major faults, but the presence of a single intrusion is not indicative of emplacement along a fault. It would be more diagnostic if multiple intrusions were identified and a more concrete emplacement method could be suggested, however until more intrusions are observed in the HALIP plume centre region, the spatial distribution of this intrusion remains questionable.

6.6 Summary

Table 11: Summary table from modelling in four plume centre regions: Deccan, HALIP, Mackenzie and Kunene-Kibaran LIPs.

	Geophysical anomalies				Intrusions from modelling						
<i>LIP /age</i>	<i>Evident from/ Amplitude</i>	<i>Label/ Figure</i>	<i>Size</i>	<i>Distance from P.C.</i>	<i>Width top (km)</i>	<i>Thickness (km)</i>	<i>Limiting Depth (km)</i>	<i>ρ range (g/cm³)</i>	<i>Avg. χ (cgs)</i>	<i>R.M. (A/m)</i>	<i>Comments and source</i>
Deccan 0.06 Ga	+58 mgal	D1; Figure 55 <i>Rajula</i>	Subcircular $d = 45$ km	80-165 km	38	10	8.7	3.1	0.0001	1.0, $D = 142^\circ$, $I = 52^\circ$	– this study
	+42 mgal	D2; Figure 55 <i>Politana</i>	Subcircular $d = 35$ km	90-215 km	31	10	8.5	3.0	0.0010	1.0, $D = 142^\circ$, $I = 52^\circ$	– this study
	+65 mgal	D3; Figure 55 <i>Vallabipur</i>	Subcircular $d = 40$ km	120-270 km	40	9	8.5	3.1	0.0010	1.0, $D = 142^\circ$, $I = 52^\circ$	– this study
	+60 mgal	III; Figure 552 <i>Porbander</i>		265-360 km	18	17.5	0	2.88	0.0025	0.8, $D = 337^\circ$, $I = -38^\circ$	- 1
		II; Figure 552 <i>Junagadh</i>			14	15.5	2	2.9	0.0025	0.7, $D = 340^\circ$, $I = -50^\circ$	- 1
	+70 mgal	D5; Figure 55 <i>Bombay</i>	Elongated 140×60 km	170-190 km	25 x 300	12	6	2.9			D5, D6 and D7 modelled as a single body - 2
	+50 mgal	D6; Figure 55 <i>Surat</i>	Subcircular $d = 35$ km	60-250 km							
	+40 mgal	D7; Figure 55 <i>Surat</i>	Subcircular $d = 35$ km	80-380 km							
	+30 mgal	Hi; Figure 551 <i>Hirapur</i>			6.5 x 20.0	9.0	6.0	2.97			- 2
	+25 mgal	Kh; Figure 551 <i>Khajuria Kalan</i>			6.0 x 26.0	13.0	6.0	2.97			- 2
	+50 mgal	Uj; Figure 551 <i>Ujjain</i>			10.0 x 18.0	13.0	8.0	2.97			- 2

<i>LIP /age</i>	<i>Evident from/ Amplitude</i>	<i>Label/ Figure</i>	<i>Size</i>	<i>Distance from P.C.</i>	<i>Width top (km)</i>	<i>Thickness (km)</i>	<i>Limiting Depth (km)</i>	<i>ρ range (g/cm³)</i>	<i>Avg. χ (cgs)</i>	<i>R.M. (A/m)</i>	<i>Comments and source</i>
Deccan (cont'.)	+10 mgal	Th; Figure 551 <i>Thuadara</i>			26.0 x 23.0	8.0	6.0	2.90			- 2
	+40 mgal	Ma; Figure 551 <i>Mandla</i>			6.5 x 26.0	15.0	6.0	2.97			- 2
	+30 mgal	Pu; Figure 551 <i>Pulgaon</i>			10.0 x 25.0	14.0	6.0	2.97			- 2
	+70 mgal	Ma; Figure 551 <i>Mahan</i>			20.0 x 28.0	15.0	8.0	2.97			- 2
	+20 mgal	Si; Figure 551 <i>Sindad</i>			15.0 x 14.0	12.0	6.0	2.97			- 2
HALIP 0.13-0.09 Ga	+850 nT	Figure 65	Subcircular <i>d</i> = 40 km	80 km	25	6	10	3.3-3.6	0.0360		- this study
Mackenzie 1.27 Ga	+54 mgal	M1; Figure 22	Elongated 200x100 km	135 km	29	16	7	3-3.3	0.0065		- this study
	+59 mgal	M2; Figure 22	Subcircular <i>d</i> = 70 km	220 km	110	15	16	3-3.2	0.0080		- this study
	+78 mgal	M3; Figure 22	Elongated 85 x 50 km	226 km	80	18	14	3.2	0.0810		- this study
	+49 mgal	M4; Figure 22	Subcircular <i>d</i> = 70 km	160 km	55	12	12	3-3.3	0.0770		- this study
	+60 mgal	M5; Figure 22	v-shaped 110 x 100 km	180 km	65	10	12	3-3.2	0.0075		- this study
	+52 mgal	M6; Figure 22	Subcircular <i>d</i> = 90 km	260 km							complexity in geophysics and geology; positioning and amplitude indicate similar origin as M1-M5 - this study

<i>LIP /age</i>	<i>Evident from/ Amplitude</i>	<i>Label/ Figure</i>	<i>Size</i>	<i>Distance from P.C.</i>	<i>Width top (km)</i>	<i>Thickness (km)</i>	<i>Limiting Depth (km)</i>	<i>ρ range (g/cm³)</i>	<i>Avg. χ (cgs)</i>	<i>R.M. (A/m)</i>	<i>Comments and source</i>
Kunene- Kibaran 1.38 Ga	+120 mgal	LV1; Figure 37	Elongated 220 × 90 km	470 km	90	7	22	3.1-3.4			- this study
	+50 mgal	LV2; Figure 37	Elongated 140 × 80 km	520 km	80	5	18	3.2-3.4			- this study
	+75 mgal	LV3; Figure 37	Elongated 200 × 100 km	560 km							along the western branch of the EARS. - this study
Average	Gravity 52 mgal		$d = 82$ km	240 km	44	12	8.5	3.9	0.0220		

Note: **P.C.** – plume centre, **ρ** – density, **χ** – magnetic susceptibility, **R.M.** – remanent magnetization, **1** – Chandrasekhar et al. (2002), **2** – Bhattacharji et al. (2004). In the case of the Deccan LIP, distances are measured from plume centres 2 and 3 (Figure 47), respectively. Limiting depth refers to the top of the body.

7 Discussion

With the goal of advancing the current understanding of LIP plumbing systems, this study has focused on prominent gravity and magnetic anomalies that are proximal to plume centre regions. The reason for this approach is the expectation that such regions will host a large number of mafic-ultramafic intrusions given that they have experienced high temperatures and feature large volumes of partial melting. The greatest difficulty in applying this method arises when correlating the source of a geophysical anomaly with a specific LIP. Typically, intrusions are geochemically linked with a LIP or correlated via dating techniques, however these methods are not possible when investigating intrusions that are not exposed at the surface and have not been accessed via drillcore. Our approach has been to select large gravity and magnetic anomalies (at least +30 mgal for gravity and $\pm$ several hundred nT for magnetic anomalies) that are spatially associated with the plume centre region (i.e. within approximately 500 km of the plume centre). Herein, we assumed that intrusions that are proximal to the plume centre are most likely associated with the LIP belonging to that plume centre. We also sought to test which of these intrusions are linked to the plume centre by whether they have any simple geometric distributions in the plume centre region. For example, we were particularly interested in anomalies that circumscribe a plume centre or that are linearly aligned along rift systems.

7.1 General Observations from Modelling

Intrusions modelled in the present study are on average 30 - 50 km wide and 10 - 15 km thick (Table 11), which are regional-scale intrusions and represent major components of LIP plumbing systems. For instance, these intrusions compare in size to some of the largest mafic-ultramafic

intrusions around the globe, some of which are known Ni-Cu-PGE producers. Some examples include the 50 km wide, 17-19 km thick Freetown igneous complex in Sierra Leone (Mgbatogu et al., 1987), the > 30 km wide and 1.5 km thick Fish-Lake and Tangle mafic-ultramafic sills of the Nikolai Greenstone mafic LIP (Glen et al., 2011), and the 500 km wide, 7-9 km thick Rustenburg layered suite of the Bushveld intrusion (e.g. Cawthorn 1996). We are therefore confident that we are investigating intrusions that form a major component of LIP plumbing systems and which are representative of LIP plumbing systems globally.

The depth to the intrusions investigated in this study vary and intrusions are modelled in all levels of the crust (near surface to >20 km depths in the lower crust). Within a given LIP, however, the depth to the intrusions tends to remain consistent, indicating that large intrusions are generally emplaced at similar levels for a given event. For instance, the shallowest intrusions are modelled within the Deccan LIP in India, where all of the intrusions (in this study and in previous studies) are modelled at depths of < 10 km, in the upper crust. On the other hand, deeper intrusions are modelled at Mackenzie, HALIP and Lake Victoria, where most of the intrusions are situated in the mid-lower crust (Table 11). This is generally attributed to density controls on the buoyancy of the mafic and ultramafic magma, however erosion surely also has a major impact on the depth to the intrusions and is one of the mechanisms responsible for a variation in depths between LIPs. The level of erosion in these regions is usually difficult to estimate and it is therefore difficult to directly compare the depth of emplacement at different locations, however there does appear to be a distinction between the shallow, smaller and less dense intrusions at Deccan as opposed to the deeper, larger and higher density intrusions at HALIP, Mackenzie and Lake Victoria.

There is a link between the size of an intrusion and its depth, where the largest intrusions are generally emplaced deeper in the crust. In this study, the smallest intrusions (~ 30 km wide) belong to the Deccan LIP and are positioned in the upper levels of the crust near the paleo-surface, while the intrusions modelled deeper in the crust at Mackenzie, HALIP and Lake Victoria are generally larger (avg. ~ 45 km wide). Alternatively, intrusions of this scale are not always located at deep crustal levels, such as is observed at Deccan. Similar near-surface intrusions have been noted to occur within other LIPs as well. A notable example is within the North Atlantic Igneous Province (NAIP), where more than 10 moderately-sized gabbroic complexes (of Deccan-scale) are exposed along the eastern margin of Greenland (Tegner et al., 1998; Callot et al., 2001).

In terms of rock composition, the intrusions modelled within the Deccan LIP have typical densities consistent with mafic rock, ranging from 2.9 to 3.1 g/cm³. The larger intrusions at Mackenzie, HALIP and Lake Victoria have much higher densities that range between 3.0 and 3.4 g/cm³ that is suggestive of an additional ultramafic component at their base. Modelling also indicates moderate to high magnetic susceptibility values overall, with average values of 0.022 cgs (0.28 SI) for all intrusions investigated. We interpret that the high magnetic susceptibility values observed for the anomalies associated with the HALIP and Mackenzie plume centres tend to be associated with the lower ultramafic portions of the intrusions. This is most apparent at HALIP, where magnetic susceptibility values of 0.036 cgs (0.45 SI) in the ultramafic rock are inferred from modelling. Given that the average magnetic susceptibility for ultramafic rocks is 0.012 cgs, or 0.15 SI (Telford et al., 1990), the unusually high magnetic susceptibilities in the ultramafic portion of the intrusions indicate serpentinization of the ultramafic rock. Similar magnetic susceptibilities are observed in some of the Mackenzie intrusions, namely M3 and M4 (Figure 22), where the lower

ultramafic components have magnetic susceptibility values of 0.13 and 0.15 cgs (or 1.6 and 1.88 SI), respectively. Modelling therefore indicates secondary magnetite production resulting from serpentinization in the ultramafic rocks, which is expected for large differentiated intrusions (e.g., Clark et al., 1992).

7.2 Distribution of Intrusions in Plume Centre Regions

In addition to the large size and amplitude of gravity and magnetic anomalies that can be used to link the buried intrusion with LIP-scale magmatism, a correlation can also be established from the proximity of the anomalies to the plume centre and their spatial distribution within the plume centre region. We find several types of intrusion patterns and group them into three types: multiple intrusions that circumscribe the plume centre, multiple intrusions aligned along rifts that may converge toward the plume centre, and single or unclassified intrusions (Figure 68), which are represented in the case studies at Deccan, HALIP, Mackenzie and Lake Victoria.

7.2.1 Intrusions with Circumferential Distributions

Intrusions that circumscribe a plume centre (Figure 68a) are most apparent within the Mackenzie and Kunene-Kibaran LIPs. We have explored in some detail the 1270 Ma Mackenzie example and confirmed the initial insights from Baragar et al. (1996) about a ring of five mafic-ultramafic intrusions located at a distance of 250 km from the plume centre (Figure 22, section 6.2). In addition, we have identified a sixth gravity anomaly that is similar in amplitude and size and that further completes the ring of intrusions

At Lake Victoria in East Africa, two (and possibly three) large mafic-ultramafic intrusions are similarly positioned at several hundred kilometers from a potential plume centre belonging to the c. 1380 Ma Kunene-Kibaran LIP (Figure 37, section 6.3). Unlike the Mackenzie intrusions that form a nearly-complete circle around the plume centre, the Lake Victoria intrusions only partially circumscribe the plume centre and notably occur along the outer periphery of a 180° giant arcuate dyke swarm.

Interestingly, no such circumferential swarm is confirmed at the Mackenzie plume centre, but given the similarities between the emplacement of intrusions at Mackenzie and Lake Victoria, we expect that a similar circumferential dyke swarm, potentially spanning 360° , may exist at Mackenzie but has not yet been observed through mapping or aeromagnetic surveys as it remains buried under a thick sequence of younger cover rocks. We do however observe narrow (approx. 10 km across) arcuate gravity anomalies that circumscribe the plume centre linking the major intrusions. This is best observed between anomalies M1 and M2, and M3 to M6 (Figure 22) and we have interpreted these to be the expression of a circumferential dyke system similar to the LVDS.

The current understanding, based largely on work by Baragar et al. (1996), is that circumferential intrusions near a plume centre are strongly linked with plume-generated regional-scale domal uplift that leads for the formation of an apical graben and normal faulting that facilitates the magma's ascent following central collapse (Figure 31, section 6.2). This is not the only mechanism that could produce the circumferential features observed at Mackenzie and Lake Victoria, however. Additional mechanisms include the presence of a large underlying magma chamber that would ultimately lead to the formation of ring dykes, or through loading by volcanic edifices (Mäkitie et al., 2014; Ernst et al., 2001). In the case of the underlying magma chamber, Mäkitie et al. (2004) have demonstrated that such a chamber would have to be unrealistically large (several hundred kilometers across), and such a chamber would be observable from regional-scale gravity surveys, but no such chambers are detected. Similarly, no evidence of loading by volcanic edifices is observed at the Mackenzie and Lake Victoria centres. Furthermore, the positioning of the Mackenzie and Lake Victoria intrusions at 250 – 500 km from the plume centre is supportive of

domal uplift that typically forms at similar scales of several hundred kilometers (Burov and Guillou-Frottier, 2005).

An additional observation comes from a comparison of the discrete set of intrusions at Mackenzie and at the Lake Victoria plume centres. At Mackenzie, magma pooled into 5 to 6 discrete intrusions (M1-M6) along a circumferential system, equally spaced around the plume centre. A similar observation is made at Lake Victoria, where 2 to 3 intrusions (LV1, LV2 and possibly LV3) are nearly equally spaced around 180° of the plume centre. This positioning is indicative of emplacement at the intersection of the circumferential pattern with linear features trending towards the plume centre. We interpret that the Mackenzie and Lake Victoria intrusions were emplaced at the intersection of circumferential systems and rifts, towards which magma was primarily channeled (see Figure 30 and Figure 47).

In conducting our global survey of geophysical anomalies in plume centre regions, we anticipated finding several cases resembling the Mackenzie circumscribing intrusions. The intrusions at the Lake Victoria plume centre of the Kunene-Kibaran LIP may represent a second example, but we do not immediately recognize additional examples. This may be due to the rarity of this type of distribution, or it may simply be that other examples are not as well preserved and less easily recognized. Nonetheless, this configuration of intrusions circumscribing a plume centre appears to be rare, and the Mackenzie LIP remains the only example of a nearly 360° ring of intrusions around its plume centre.

7.2.2 Intrusions emplaced along Linear Rift Systems

One of the best examples of intrusions emplaced along rift structures (Figure 68b) is within the Deccan Traps, India. Here, more than eight predominantly mafic intrusions linked with Deccan magmatism are situated along the E-W trending Narmada-Tapti rift through central India (Figure 51, Table 8; Bhattacharji et al., 2004). There are also Deccan-related intrusions along the West Coast rift near Mumbai (Bombay), observed as +30 to +70 mgal circular to elongate gravity anomalies along the West Coast rift that are modelled as a single 12 km wide and 300 km long intrusion that extends along the length of the West Coast rift.

We have additionally explored three gravity anomalies along the western margin of the Gulf of Cambay (Figure 55) and have confirmed the initial insights by Chandrasekhar (2002) about a series of mafic bodies along the edges of the Cambay rift basin, with density estimates from modelling of 3.0 to 3.1 g/cm³ and located at shallow depths in the upper crust. Their association with NE-SW oriented rift structures indicates a deep-seated fault or fracture, or rift along which they were emplaced (Chandrasekhar, 2002).

This type of linear distribution along a rift structure is not unique to the Deccan LIP. Once again considering the intrusions along the Greenland margin, there is a distinct relation in the distribution of intrusions along linear features, particularly in regards to the spacing of these intrusions. In the case of the Deccan LIP, the intrusions emplaced along the western and eastern edges of the Cambay rift basin are spaced at 50 km intervals. Similarly, the intrusions along the western Greenland are emplaced at roughly 40 km intervals. As mentioned previously, these intrusions are relatively small (about 30 km across), they are emplaced at shallow levels in the crust and are generally mafic in composition (Tegner et al., 1998). Also, similarly to the intrusions in the Deccan Traps, the mafic

intrusions along the eastern Greenland margin are underlain by deeper ultramafic components (Larsen et al., 1997).

The significance of these relatively small and regularly spaced intrusions along rifts may be reflective of an underlying and uniformly distributed magma source for the intrusions, such as magmatic underplating. Additionally, the presence of features that preferentially channel magma to only a few locations (e.g., the Lake Victoria intrusions), or alternatively along many conduits (such as along extensive rift structures in the Deccan LIP), likely has a drastic impact on the number and size of the intrusions. In the case of Lake Victoria, where magma is preferentially channeled to a few locations only, the intrusions are generally much larger (80-90 km across in the Lake Victoria case vs. < 20 km across for Deccan) and are emplaced deeper into the crust (18-22 km depth for Lake Victoria vs. 6-8 km depths for Deccan), indicating that larger volumes of magma were channeled towards a select few locations. It is therefore concluded that the magma that fed the smaller, shallower, more widespread intrusions near a plume centre are widely distributed in the crust as a result of a combination of extensive magmatic underplating and an increased number of pathways along which the magma can ascend.

7.2.3 Unclassified Intrusions

In many of the plume centres investigated, intrusions are identified near a plume centre that are not distributed into distinct configurations that would imply a plausible emplacement mechanism, such as those that were identified along circumferential or linear features. These intrusions may be independent of a structural control and represent large amounts of magma emplaced at random in the plume centre region. However, we also consider the possibility that these intrusions are components of the first two types. In the latter case, a single intrusion may

represent a component of circumferential or linear structures, but until additional intrusions are identified in these regions it is not clear whether these are single intrusions or are part of a larger structure and so we consider them for the time being as unclassified (Figure 68c).

The High Arctic LIP (HALIP) is a prime example. A single intrusion is identified on western Ellesmere from a + 850 nT magnetic anomaly. A second intrusion of similar scale is located on the northern edge of Ellesmere Island, the Wootton intrusion, which is identified from field observations and is not detected from regional-scale magnetic maps used in the present study. Both intrusions are inferred to have been emplaced at separate stages of HALIP magmatism (section 6.5.3). It remains unclear whether these intrusions are correlated by a structural control, or if they are components of a larger system of layered intrusions that remains undetected using geophysical methods. In the case of the intrusion on western Ellesmere Island, it is possible that this is the only intrusion whose geophysical signal is not obscured by the host rocks, due primarily to its unusually high magnetic susceptibility.

Given the large volumes of magma involved in the formation of the HALIP, it is unlikely that these were the only two intrusions of their kind emplaced during the multiple stages of HALIP magmatism. Another example of such an intrusion is the funnel-shaped mafic-ultramafic intrusion in the Cuddapah basin, identified from gravity data and associated with the 1.9 Ga Cuddapah-Bastar LIP in India (Grant, 1983; Chatterjee and Bhattacharji, 2001; Ernst and Srivastava, 2008; French et al., 2008). In both cases, it seems more likely that these are components of a larger system of intrusions, and we predict that in the cases where only a single major intrusion is observed (e.g. High Arctic and Cuddapah-Bastar LIPs), more detailed ground or geophysical surveys will reveal additional intrusions. Nevertheless, we provide two potential explanations for the formation of a single or multiple

intrusions that do not follow a clear geometrical configuration: 1) It is possible that a lack of extensive underplating in a region could drastically decrease the number of intrusions emplaced in the plume centre region, since the distribution of magma through underplating favors upwelling along multiple planes of weakness as opposed to a single location directly above the centre of the plume head, and 2) Uplift plays an important role in the genesis of linear/radial and circumferential features near a plume centre, such that regions that did not undergo drastic uplift may not have formed an extensive system of pathways through which magma would have ascended. Therefore, a plume that did not lead to extensive magmatic underplating and/or plume-generated domal uplift may result in a significantly less-developed plumbing system.

Figure 68: Spatial distribution of layered intrusions in plume centre regions: a) Multiple intrusions circumscribing the plume centre with a radius of about 200-500 km (e.g., Mackenzie LIP), b) Linear distributions of layered intrusions associated with rifting that may converge towards a plume centre (e.g. Deccan LIP), and c) Single intrusion within a few hundred kilometers of the plume centre (e.g., HALIP, Arctic Canada). Red star represents the plume centre. Black circles represent layered intrusions.

7.3 Final Comments and Modelling Limitations

It is important to note that geophysical modelling is an interpretative technique and, as such, it has its limitations. For instance, numerous geologically-reasonable models can reproduce a given geophysical data set and therefore confidence in a model arises from including constraints as well as considering the most geologically-plausible scenarios for a given anomaly. In this study, crustal layer thickness and density estimates from seismic studies (CRUST1.0), and first-order approximations of the causative bodies (intrusions) are incorporated into modelling to help constrain the model. Nevertheless, certain parameters are better constrained using geophysical modelling than others. For example, the best constrained parameters are density and limiting depth estimates (depth to the upper surface). This is a direct consequence of the drastic density contrast between mafic-ultramafic rocks and the surrounding country rock that produces strong gravity anomalies, as well as the tendency for density to increase with depth, thus lowering the density contrast between intrusion and host rock and making the lower extent of the intrusions harder to resolve. Nevertheless, density and depth estimates are able to answer the most pressing questions we aim to answer in the current study; mainly the composition and depth to the intrusions.

An interesting and perhaps surprising aspect that is observed from this study is that although small mafic-ultramafic intrusions (less than a few km in diameter) do occur above plume centres (for example, the mafic-ultramafic intrusions of the Kabanga-Musongati lineament at Lake Victoria, Africa), we do not map any large intrusions (> 30 km in diameter) directly above the plume centre. Instead, we find that these tend to be situated at just over 250 kilometers from the plume centre (Table 11), suggesting that the ascent of magma leading to the formation of intrusions in the crust is not greatest directly above the focus of the plume, but instead is channeled laterally and pooled at

several hundred kilometers from the plume centre. Within the Mackenzie LIP, this is reflected by the positioning of intrusions at several hundred kilometers from the plume centre. Also, radial dykes at Mackenzie do not extend all of the way to the focus of the swarm, but instead extend only to about 250 km from the centre, at the same distance as the intrusive bodies. In contrast, it is interesting to note that radiating dyke swarm systems on other planets (e.g., Venus) tend to converge to a very tight centre region, which could imply that a large intrusion is situated at the centre acting as the magma source for the dykes (Ernst et al. 2003). It has been suggested that the fractures at Mackenzie extend all of the way to the plume centre, but magmatism only feeds the intrusion starting at several hundred kilometers from the plume centre. A major difference on Earth (as opposed to Venus) is associated rifting (successful or not) that would obscure the absolute plume centre as magma is upwelled along rift structures above the plume centre region.

We also draw attention to intrusions like the Muskox intrusion on the Arctic Mainland in northern Canada, which is linked with the intrusion at M3 (observed from magnetic and gravity data). Such a link indicates that the large chambers that are modelled surrounding the Mackenzie plume centre may have also produced secondary chambers that are not immediately apparent as bodies of interest (i.e. targets for exploration) when analyzing geophysical data at regional scales, but which become apparent when considered with respect to large intrusions that are apparent at the current scale. For instance, in the case of the Muskox intrusion, a gravity signal is observed but is not immediately obvious at regional-scales as being caused by a major intrusion related to the Mackenzie LIP. It only becomes apparent when its relation to the intrusions at M3 is considered. This may be due either to their size or to their lack of density or magnetic susceptibility contrast with the host rocks. Nevertheless, although the intrusions identified using the methods outlined in the

present study do not represent targets for exploration, their link with economic targets can have implications for exploration.

8 Conclusion and Recommendations for Future Work

The analysis of regional-scale gravity and magnetic data has proven to be an effective means of identifying and characterizing mafic-ultramafic intrusions linked with LIPs that remain buried and form a large component of the plumbing system, but would otherwise not be recognized through field observations. Furthermore, we find that the best ways in which these intrusions can be confidently correlated with a LIP are primarily from their spatial distribution (including proximity to the plume centre), as well as their large sizes, circular-oval shapes and associated high-amplitude geophysical anomalies. In the present study, gravity and magnetic data in 18 mantle plume centre regions distributed globally are investigated in order to identify large (> 30 km diameter) mafic-ultramafic intrusions that can be confidently linked with a LIP. These include mainly Proterozoic and Phanerozoic examples and have been identified on the basis of their spatial association with Large Igneous Provinces (LIPs).

Based on observations within these 18 plume centre regions, spatial distributions of layered intrusions can be classified into three major categories: 1) intrusions that circumscribe a plume centre and which are emplaced at the intersection of radial and circumferential fractures (formed as a result of plume-induced uplift and subsequent subsidence), typically located at 200–500 km from the plume centre and spaced at equal intervals around the plume centre, 2) linearly aligned intrusions emplaced along rifts, in some case along triple junction rift arms, and 3) single or unclassified intrusions, which may also be a portion of a circumferential or radial distribution, but additional intrusions in the region have not yet been identified. An in-depth investigation of the spatial distribution of intrusions within select LIPs has led to new insights into their formation, and

can also be used to identify or act as supporting evidence towards the identification of a plume centre location.

From the 18 plume centre regions investigated, eleven prominent, regional-scale geophysical anomalies are modelled within four LIPs that were selected for detailed study: the 1270 Ma Mackenzie LIP in North America, the c. 1380 Ma Kunene-Kibaran LIP in East Africa, the 66 Ma Deccan LIP in India, and the 130-80 Ma High Arctic LIP (HALIP) in Arctic Canada. The key results are summarized here:

Two cases of circumferential intrusions are identified from the global survey of LIPs: the 1270 Ma Mackenzie LIP in North America, and the 1380 Ma Kunene-Kibaran LIP in East Africa. From interpretations of gravity and magnetic data, five layered intrusions, and possibly a sixth, circumscribe the Mackenzie plume centre over a span of 310° and are located at an average distance of 200 km from the plume centre. The plume centre, initially recognized at the focus of a radiating dyke swarm, is found to lie at the centre of this ring of intrusions, and is coincident with a prominent magnetic anomaly (~ 250 km across) that is inferred to mark expansive magmatic underplating in the plume centre region. Similar intrusions are identified for the first time within the Kunene-Kibaran LIP from gravity data, which are interpreted as mafic-ultramafic intrusions. These are positioned on the outer periphery of a 180° giant arcuate dyke swarm (LVDS) at approximately 500 km from the centre, and are supporting evidence towards a plume centre located at the centre of the LVDS. Gravity data also delineates rift structures that converge towards the centre of the LVDS and are interpreted as a triple junction rift system with a plume centre at the intersection, thus further supporting a central plume location.

Three primarily mafic intrusions are characterized within the Deccan Traps in India that are located along rift structures that converge towards a postulated plume centre at the intersection of the Cambay and Kutch rift systems and otherwise supported by seismic data, Deccan intrusive rock outcrops, and its location along the Réunion hot spot track. From modelling, remanent magnetization values obtained through modelling herein indicate normal polarities, and as such, these intrusions are considered to be a component of the first stage of Deccan magmatism during magnetic chron C30n, and emplaced coevally along N-S rifts related to the formation of the gulf of Cambay. These intrusions, along with similar intrusions along the eastern edge of the gulf of Cambay, are considered as being aligned towards a potential plume centre location to the north of Cambay and the main component of the Deccan flood basalts.

Lastly, intrusions are identified that cannot be related to their plume centre via any clear geometrical pattern that may indicate a plausible means for their emplacement (e.g., the HALIP magnetic anomaly on Ellesmere Island, North America). Until such time as extensive studies of these remote areas can either confirm or refute the existence of additional intrusions in these regions, we consider these as likely components of circumferential or linear distributions which have not yet been identified.

Herein, we have established a basis by which layered intrusions can be identified and confidently correlated with a given LIP. The main strengths of this method are the accessibility of appropriate data and the vast areas that can be investigated that allows for global surveys. This method also shows great potential as a tool for identifying buried components of LIP plumbing systems that have not previously been recognized through geological surveys. Provided the accessibility of regional-scale geophysical data, implementation of this technique can lead to a

drastic increase in the understanding of this component of the plumbing system. We therefore propose that future investigations of LIP plumbing systems, particularly within the plume centre region, should be focused on applying these data sets to the identification of intrusions within other LIPs from the global LIP database. In addition, numerous anomalies were identified in the present study, but were not considered for detailed modelling because their source and relation to a LIP was uncertain (based on various factors, but which primarily included complex geology in the region that makes any geophysical interpretation ambiguous). We therefore also propose that these anomalies be reinvestigated and further considered as potential expressions of layered intrusions linked with LIPs. Lastly, we propose that the spatial distribution types detailed herein be generally applied to studies of LIP plume centre regions.

9 References

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