Volcanic Architecture and Mineral Prospectivity of the Central Kalkarindji CFBP, Australia

1st Year Probation Report

Peter Marshall

Supervision Team:
Dr Mike Widdowson, Prof. Simon Kelley, Dr David Murphy (QUT)

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Abstract

The Kalkarindji continental flood basalt province of northern Australia is one of the lesser known large igneous provinces in the world. This project aims to establish a volcanic architecture of the central zone by employing five different analytical techniques, in 5 sub-projects. Each project will address a series of objectives, with an eventual aim of being able to display a complete geological narrative for the region.

Preliminary work is presented from the first project comparing volcanostratigraphy of three boreholes drilled in 1970 across a 600 km^2 area SE of Lake Argyle. Initial data shows agreement with previous studies on the province's composition of a tholeiitic basaltic andesite. Detailed inspection of core-chip material combined with detailed geochemistry provides a method for flow-unit identification and thus the basis for correlating over distances of c. 100 km. Comparisons between these logs reveal insights to both correlative stratigraphy and larger-scale eruption mechanics within this central region.

1. Introduction

Continental flood basalt provinces (CFBPs) are a subset of Large Igneous Provinces (LIPs) occurring as large constructs of basaltic lava on continental crust and characterised by huge areas of lava (> 100,000 sq. Km), often in thick stacked sheets, resulting from a rapid outpouring of molten material in a geologically short time span, often ~2 - 3 Ma (Gallagher & Hawkesworth, 1992). Kalkarindji is a medium sized CFBP which was erupted during the mid Cambrian period, 508-505 ± 2 Ma (Glass et al., 2006) onto the Australian craton (fig. 1).

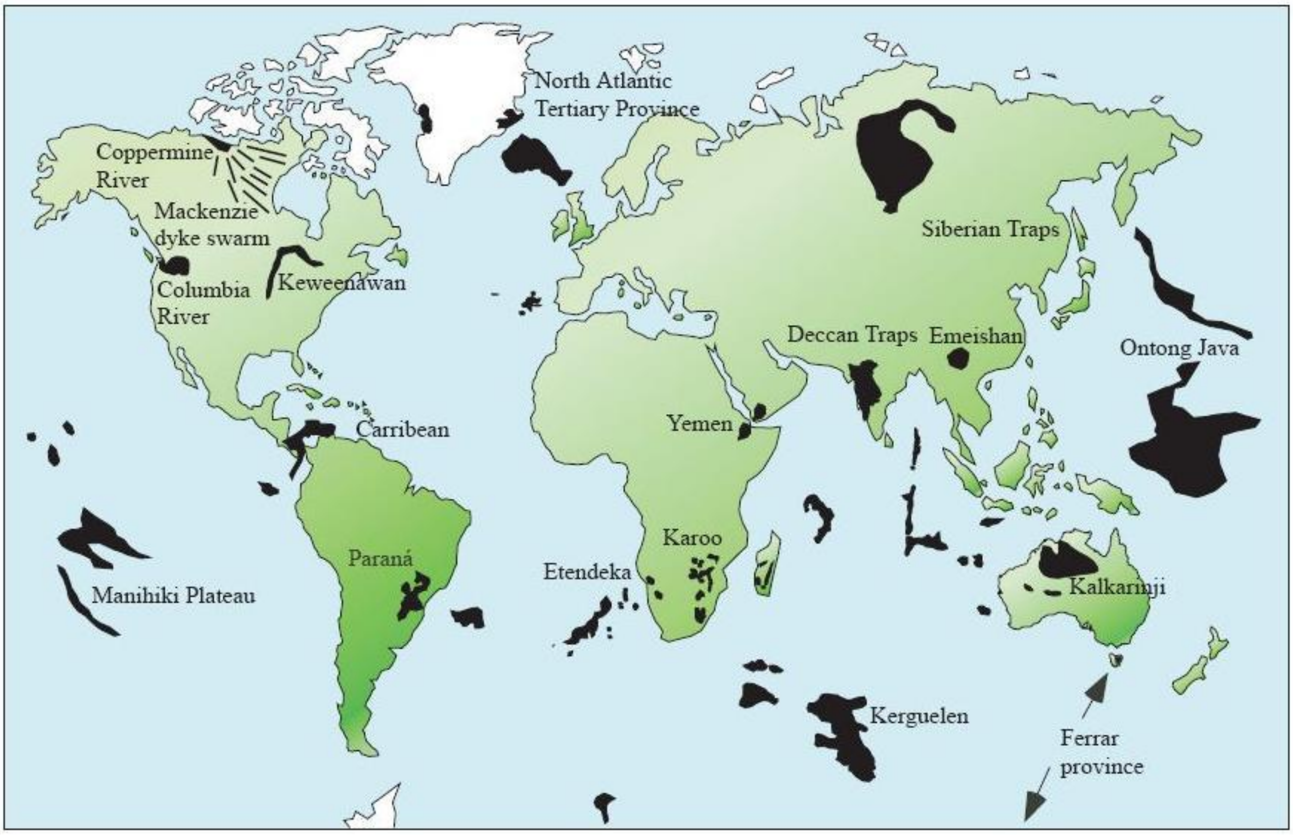


Figure 1: *Modern day global distribution of continental and oceanic LIPs. Kalkarindji is noted to cover the majority of northern Australia. (Taken from Glass, 2002, modified from Saunders et al., 1992).*

1.1. Kalkarindji

The Kalkarindji comprises 5 different volcanic regions; these being the Antrim Plateau, Helen Springs, Nutwood Downs, Peaker Piker and Colless volcanics. Each region is geographically independent of one another yet related through their geochemical signatures. Overall, the province covers a large part of the north Australian desert with a surface exposure of 425,000 km^2 (Veevers, 2001) and an inferred extent exceeding 1.5 x 10^5 km^2. However, the province enjoys an anonymity not usually afforded to structures of this size, due mainly to this remote location. Thus relatively little is known about its composition, structure, age and history due to this lack of attention, both in the public and scientific world. The main objective of this work is to change this perception by beginning to improve the understanding of the volcanic style and evolution of the province.

1.1.1. General Geological History

The Kalkarindji is the oldest known CFBP to have been erupted during the Phanerozoic. It is also one of the best preserved due to its location on the tectonically stable Australian craton. Following the break-up of Rodinia c.750 Ma (Torsvik, 2003), modern-day Australia formed part of the northern margin of Gondwana by ~540 Ma (Veevers, 2001). Over the next 40 Ma this new supercontinent gradually moved southwards (Scotese, 2003), causing Australia to straddle the equator by 500 Ma (Torsvik & Cocks, 2009). Currently dated to 508-505 ± 2 Ma via the $^{40}Ar/^{39}Ar$ method (Glass et al., 2006) and SHRIMP Zircon (Hanley & Wingate, 2000), basaltic lava is thought to have been extruded onto the edge of the continental landmass/ adjacent shallow marine shelf (fig. 2). Evidence for this tropical setting is found in the stromatolitic fringing reef strata of the Headley's and Montejinni Limestones, which although lying unconformably above the Kalkarindji (Cutovinos et al., 2002), are of mid-Cambrian age. This landmass has, since the late Cambrian, sat largely un-deformed above sea-level with very little to no tectonic disruption having occured, leaving the volcanic successions of the Kalkarindji largely undisturbed and well-preserved in many areas.

Debate still exists concerning the initiation of volcanism. Glass (2002) argues that the eruption was triggered by large scale lithospheric delamination, causing massive decompressional melting, creating deep source melts of 50-70 km. However, the eruption has also been placed radially above the edges of either the African or Pacific Large Low Shear wave Velocity Provinces (LLSVPs) in Earth's lowermost mantle (Torsvik et al., 2008) indicating a more typical mantle plume source for magma creation (Garnero & McNamara, 2008). Investigations by Glass into the Milliwindi dyke (Hanley & Wingate, 2000) show associations with main Kalkarindji geochemical signature, indicating it to be a possible feeder system now exhumed at the surface.

a)

b)

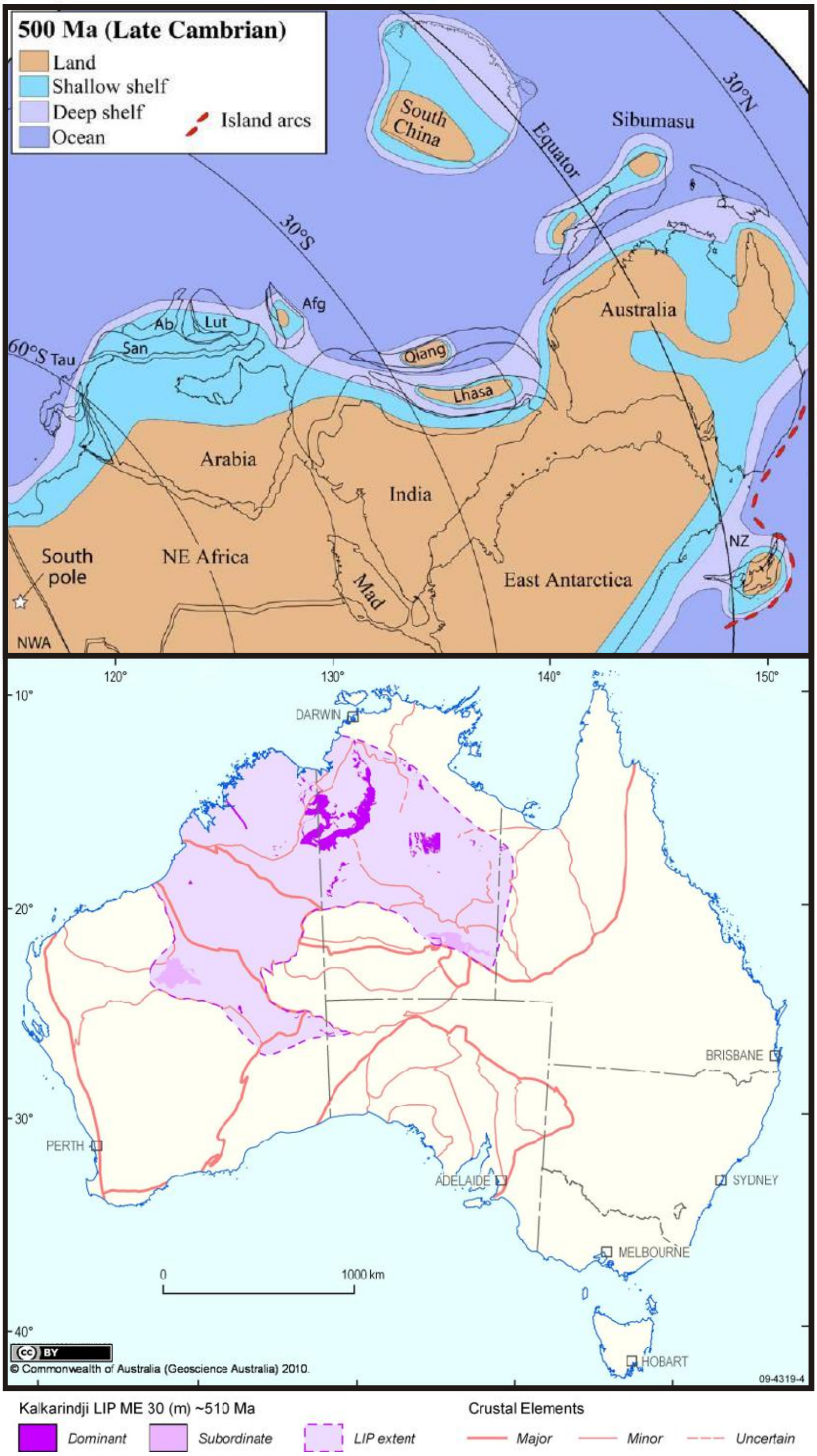


Figure 2: a) *Palaeo-reconstruction of the northern margin of Gondwana at 500 Ma showing Australia straddling the equator (From Torsvik, 2009).* ***b)*** *Map of the proposed extent of Kalkarindji defined by Glass (2002) and Evins (2009). See how the shape of eruptive extent follows interpreted palaeo-topography above. (From Geoscience Australia, 2010).*

1.1.2. Local Geology of the Central Zone

Commonly known as the Antrim Plateau Volcanics (APV), this zone is the most extensive of the exposed basalt packages in the province > 400,000 km^2 (Veevers, 2004), with the thickest successions up to 0.7 - 1.1 km (Cutovinos et al., 2002). Field reconnaissance reveals flow units to be thick (40 - 60 m) sheet-like aphanitic basalt with vesiculated or rubbly flow-tops (Murphy & Widdowson, 2011). The general geochemical characteristics of the units indicate predominantly evolved, low Ti-tholeiitic basaltic andesites and basaltic trachy-andesites exhibiting extreme crustal contamination signatures (figs. 3 & 4). Due to a lack of tectonism (discussed above) it is believed that the buried subvolcanic feeder system buried below the lava sequence may harbour large amounts of mineralisation. This theory is based around the similarities which exist between the Siberian Traps and Kalkarindji, with both displaying high-level crustally-contaminated low-Ti tholeiitic basalt melts (Murphy & Widdowson, 2011). The Noril'sk Ni-Cu-PGE deposits in Siberia are associated with major crustal faults acting as conduits for lava intrusion to shallow-depth magma chambers. Kalkarindji experiences similar faulting with the Limbunya fault, Blackfellow Creek fault and the Halls Creek orogenic belt being the proximal features within the APV which could provide such a pathway.

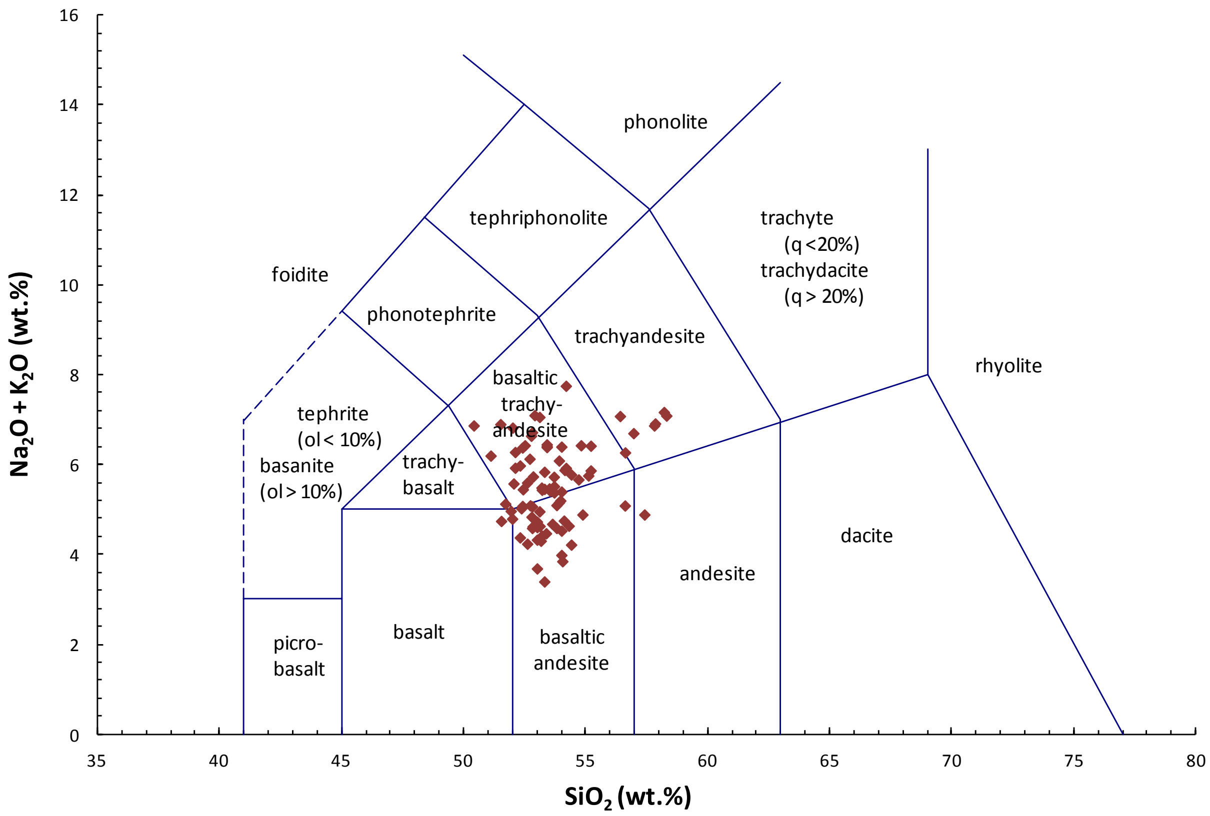


Figure 3: *Total Alkali versus Silica (TAS) plot to display the basaltic andesite chemical signature of the Kalkarindji. Samples displayed form part of investigations into the Blackfellow Creek region of Waterloo. (Clark pers. Comm. 2012).*

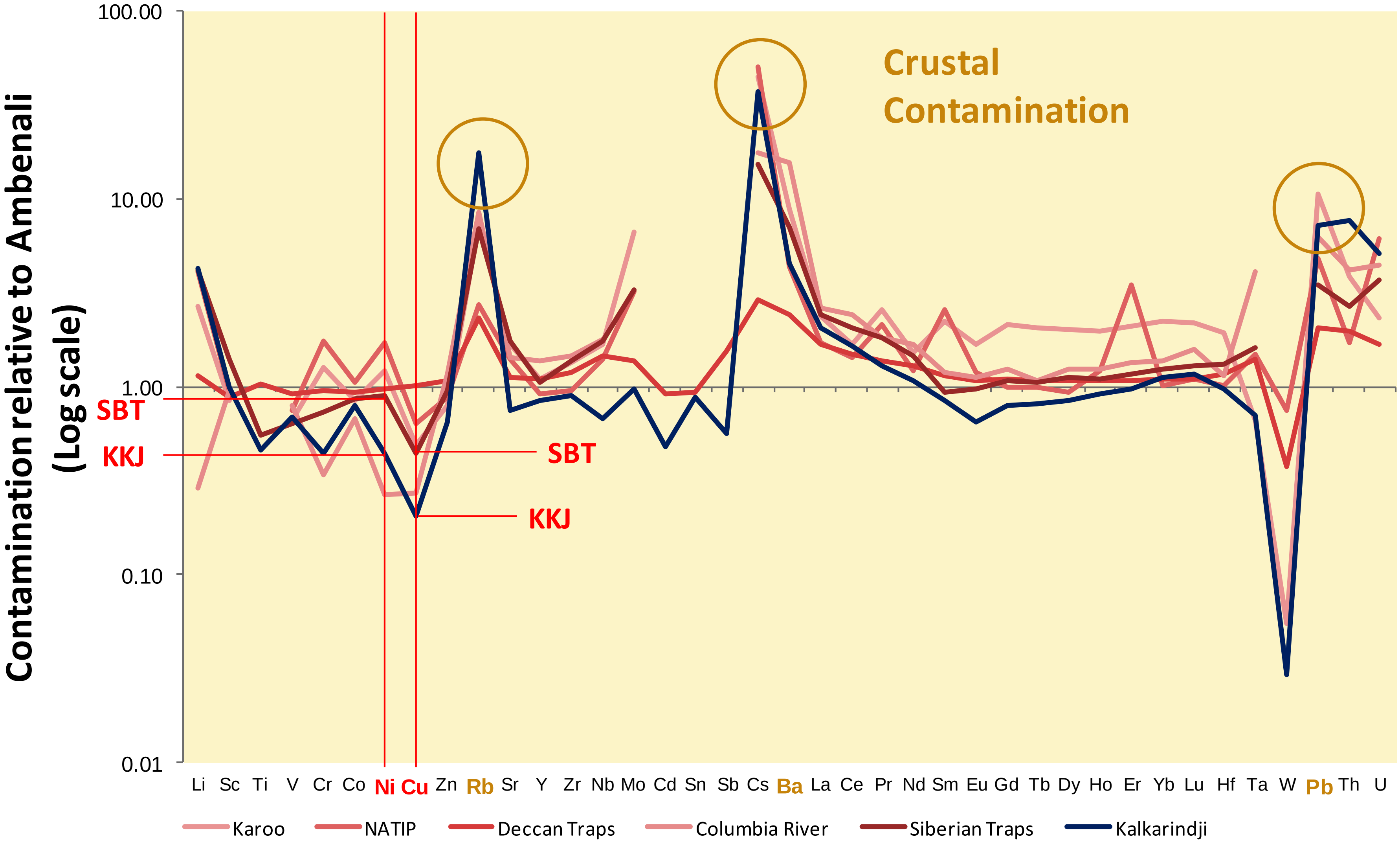


Figure 4: *Spider diagram to display the crustal contamination of Kalkarindji compared to other LIPs. On the left, a comparison between the Siberian Traps (SBT) and Kalkarindji (KKJ) for Ni and Cu, indicating KKJ should exhibit greater amounts of Ni-Cu-PGE in ore bodies deposited beneath lava successions. Spikes in Rb, Ba and Pb indicate typical shallow crustal contamination. (Data collated from GeoRoc database, Mainz, Germany and N.Clark, pers. Comm.).*

2. Aims and Objectives

2.1. General Objectives

The main aim of this research project is to build a comprehensive volcanic architecture of the Central Kalkarindji and a tectonic setting for the eruption. Accordingly, several factors need to be addressed to build a coherent story. These can be outlined as four main statements which will be addressed during the research period.

i) Establish the palaeo-environment into which the flood basalts of Kalkarindji were erupted, including palaeo-topography, palaeo-flow propagation, stacking and subsequent interaction of lava units.

ii) Characterise the eruption mechanisms in the central zone, specifically, vent locations, feeder dyke systems and mineral enrichment deposits.

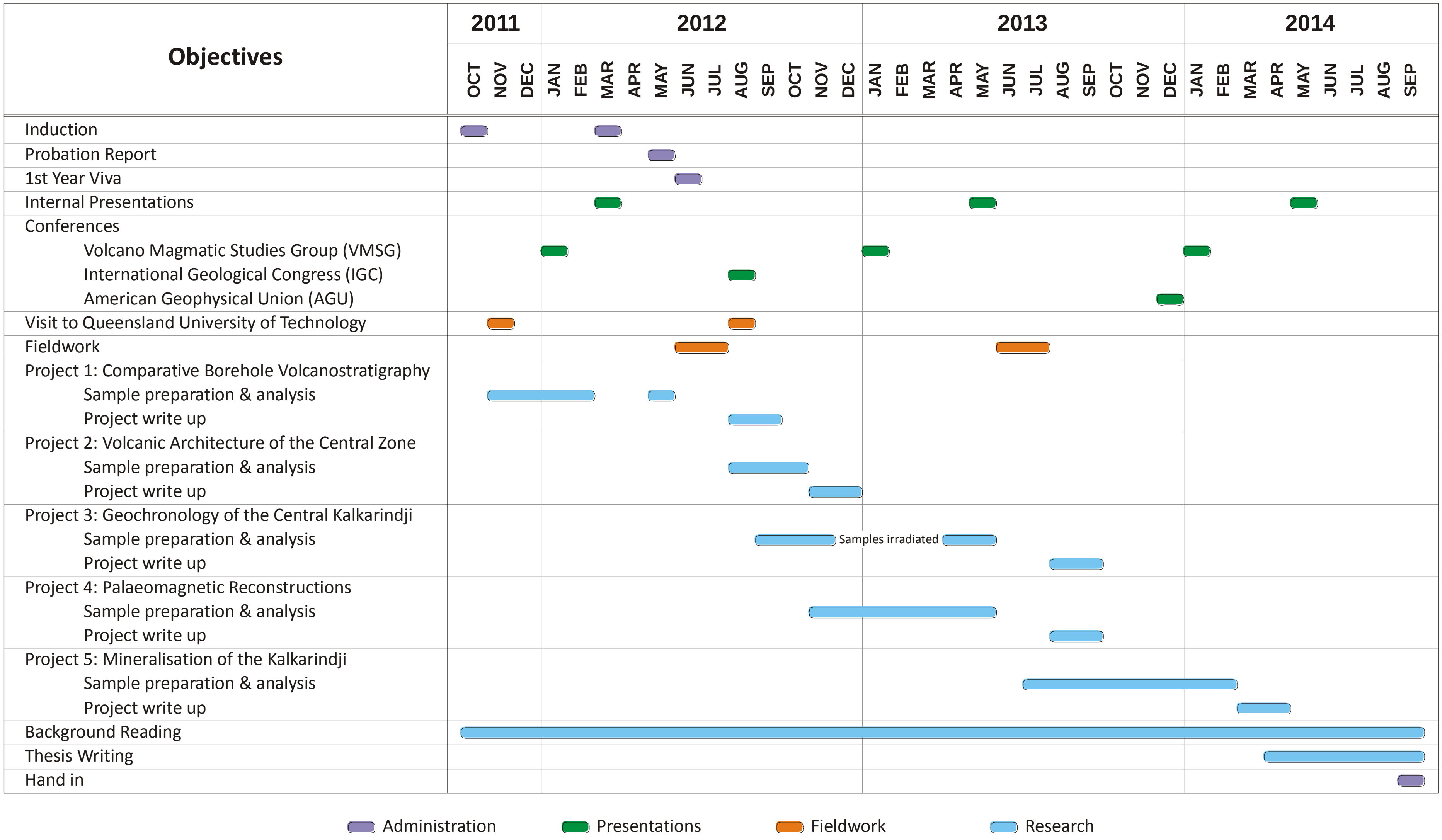
iii) Determine accurate and precise eruption timescales within the central region of Waterloo.

iv) Characterise the tectonic setting to better understand and thus provide an overview of the causes for an eruption of this magnitude.

2.2. Scheme of Work

To complete the research originally outlined, 5 sub-projects have been proposed which will fulfil the different objectives. These aim to answer individual questions and significantly improve upon the limited knowledge currently known about Kalkarindji. The Gantt chart below (fig. 5) sets out a plan of action for how time will be spent during the research.

Figure 5: *Gantt chart displaying the timescales on which the various parts of this research are planned to be undertaken.*



2.3. Overview of Proposed Techniques

For the five separate sub-projects of this research, each will use a different analytical technique to achieve answers to the questions asked. These range from basic whole rock geochemistry to palaeomagnetic reconstructions and detailed investigations into sulphur isotope sequestration.

2.3.1. Fieldwork

Two month-long field seasons will be completed with the aim of collecting samples, taking measurements and making observations related to the volcanic stratigraphy and architecture of the central zone. This will involve revision of previous work undertaken by Glass (2002), Evins (2006) and Clark (2011) in the northern Waterloo region, before an expansion of field area to the west and south, including the Panton Basin (fig. 6). Directed sampling will occur with drill core samples taken for palaeomagnetic reconstructions related to project 4, while fresh phenocrystic basalt will be sought for geochronology sample selection (project 3). The first field season will yield a detailed map of basalt outcrop, project 2, which will help to guide sample collection in the second field season for project 5.

2.3.2. Major and trace element geochemistry

Trace element geochemistry will be utilised in projects 1 & 2 (fig. 5) to create a basic geochemical base for assessing the flow hierarchy. The main technique used in project 1 has been x-ray fluorescence (XRF) at the Open University, producing both major and trace element data sets. To obtain rare earth element (REE) data, inductively coupled plasma mass spectrometry (ICP-MS) will be used; cross correlation between the two techniques will be undertaken to ensure consistency of results. These basic data will provide a basis for selecting samples for further isotope work (projects 2 & 5).

2.3.3. Isotope geochemistry

Mass spectrometry (ICP-MS) at the Open University will form the bulk of the work aimed at determining the $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$ and potentially Hf, ratios to determine the levels of crustal contamination. These ratios indicate the evolution of magma during its travels from the region of original melt generation. This will form the main data for project 2, and supplementary data in project 5. The main data for project 5 will be derived from S-isotope investigations under the supervision of Dr. Rob Newton at the University of Leeds. The aim here is to determine sequestration levels, and thus infer the amount of Ni-Cu-PGE mineral enrichment which has occurred during magma ascent and emplacement. A comparison will be drawn between the Noril'sk deposits within the Siberian Traps and Kalkarindji.

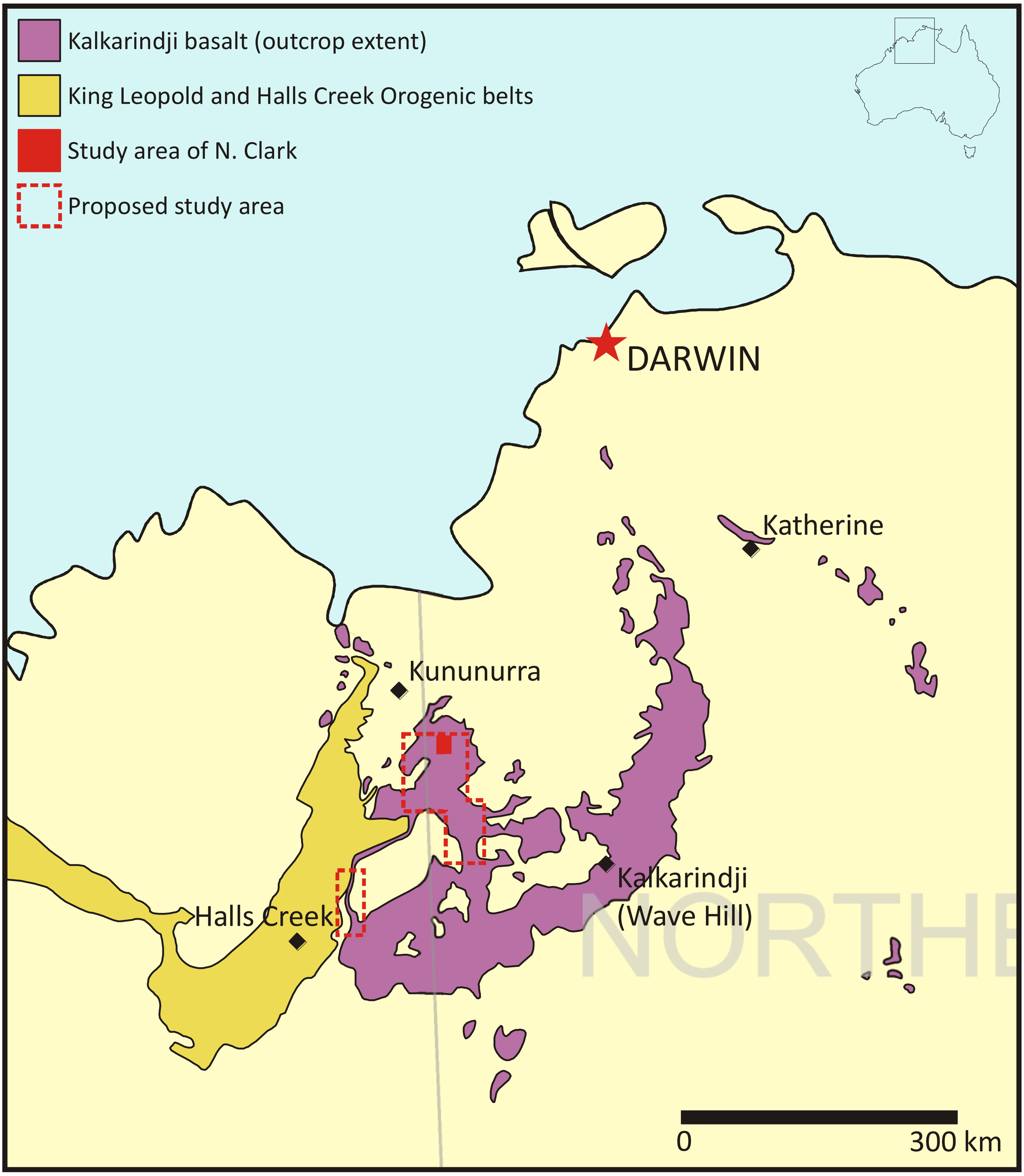


Figure 6: *Location map to show previous work undertaken in the Kalkarindji and proposed areas into which fieldwork will expand during this research, namely the Waterloo and Limbunya areas of the APV (central) and the Panton Basin (near Halls Creek).*

2.3.4. $^{40}Ar/^{39}Ar$ laserprobe geochronology

Project 3 will aim to determine an eruption timescale for a measured thickness of lava within the Waterloo region. To achieve this $^{40}Ar/^{39}Ar$ laserprobe dating by total fusion and stepped heating of mineral fractions will be undertaken in the Argon Laboratory at the Open University. This process involves the complete melting of a single plagioclase grain, either immediately or incrementally, to release Ar gas from the crystal. The analysis relies upon the measured ratio between the natural decay of ^{40}K to ^{40}Ar and the irradiation-induced decay of ^{39}K to ^{39}Ar (Kelley, 2002). Samples from the top and bottom of a measured section will be chosen with assistance from electronmicroprobe analysis (EMPA) and optical microscopy, to select the cleanest samples to reduce analytical errors.

2.3.5. Palaeomagnetic Reconstructions

The necessity for project 5 arises from the need to accurately place the Australian continent during the time of eruption. Torsvik (2008, 2009, 2011) has shown how the Australian craton formed part of the northern Gondwanan continent during the Cambrian period which was moving south following the break of Rodinia. The aim of this project will be to accurately provide palaeomagnetic data of the Waterloo region, which will aid in placing the eruption in a palaeo-geographical sense. A previous study by McElhinney & Luck (1970) displayed that there is at least one magnetic reversal within the outcrop, but these were not placed in a stratigraphic order. Thus new data, taken from differing lava flows, will allow for correlation through palaeomagnetic signatures across the field area in a similar vein to work completed on the Deccan Traps (Jay et al., 2009). This primary data is also predicted to supplement the $^{40}Ar/^{39}Ar$ dating of project 3. Secondary AMS fabric data will potentially provide palaeo-flow indicators tying in with projects 2 & 5. Drill core samples will be taken during the first field season, and analysed under the supervision of Dr. Conall Mac Niocaill at the University of Oxford.

3. Project 1: Comparative Borehole Volcanostratigraphy

3.1. Concept

The concept behind the project is to correlate flows over distances of c. 100 km, with comparisons between these logs revealing insights to both correlative stratigraphy and larger-scale eruption mechanics within this central region. This project should help to answer, in part, the first two objectives.

To achieve this aim, material was collected from the Geoscience Australia archives, specifically borehole material from BMR Limbunya 1, BMR Waterloo 1, & BMR Waterloo 2, which were drilled in 1970 under the direction of the Bureau of Mineral Resources, Geology and Geophysics (Bultitide, 1971). The holes are located in the western Waterloo region, an area SE of Lake Argyle, c. 600 km^2 (fig. 7). The project arose due to the lack of a previous correlation exercise, but inference that some holes could be seen to show similar characteristics (Bultitide, 1971). Simple trigonometry dictates that if certain flows do correlate at different stratigraphic horizons, any incline in palaeo-topography can then be inferred.

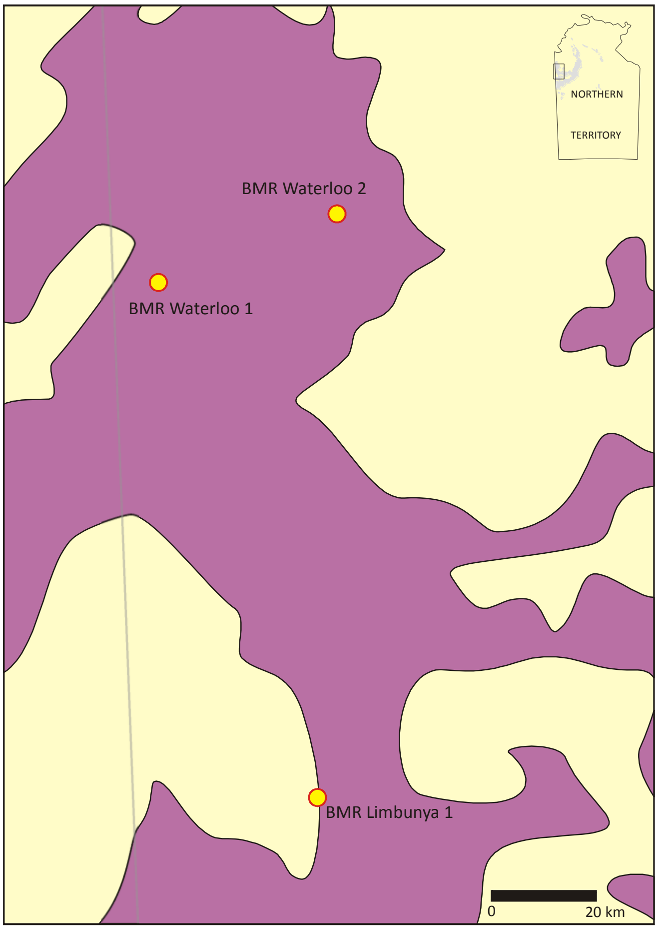


Figure 7: *Locations of the three boreholes studied in this project. The Antrim Plateau Volcanics are displayed in purple.*

3.2. Methodology

Samples were collected from the archive of boreholes at Geoscience Australia (GA), Canberra. Drilling was conducted using imperial measurement (feet and inches), subsequent labelling has followed this convention. Sampling was restricted by GA to 20g per sample. Waterloo 1 & 2 were sampled by Clark, Gray & Murphy in May 2011, whilst Limbunya 1 was sampled in November 2011 by Marshall and Gray. The analytical methodology can be split into four phases.

1) When originally drilled the borehole material was predominantly recovered as rock chips with only small sections of complete core sampled. Accordingly, these few cores often span only 10 ft (~3 m) and thus show no usefully distinctive features pertaining to the structure of a whole flow. The chipped sections were split and stored in 5 ft samples throughout the borehole; for the purpose of this study, these were visually analysed for lithology, colour, texture and grain size. A representative 20g was taken from each sample to provide a complete record of all three boreholes.

2) Using the observational data recorded during sample collection, a crude stratigraphical column was generated (fig. 8 & A1). Notational records from the original survey show the visual recognition of characteristic aphanitic basalt and vesiculated, rubbly, and often brecciated lava, also identified in the field, within this stratigraphy. As a crude guide, vesicles were taken as indicative of the top of a flow, even though it is noted that vesicles can be trapped on the underside of a lava flow (Self et al., 1997; Obata & Mizuta, 1994; Mizuta et al., 1990). This issue will be approached as part of the analysis of the geochemical data. This identification allows for a distinction to be made between 'flow-core' - aphanitic basalt - and 'flow-top' vesiculated basalt. The transfer from notational to visual representation of the stratigraphy aids in recognition of flows, by virtue of the recognition of flow tops, indicating a separation from the lava above, resulting in volcanostratigraphic column for all three boreholes from observational data alone (fig. 9).

3) Following the separation into distinct flows, directed sampling was conducted throughout the whole depth of all three boreholes. Following selection, samples were cleaned of all drilling mud which could contaminate results. A check was made on the cleaning process, by splitting 3 samples into two batches. The first batch was manually cleaned in the same process as every other sample, whilst the second batch was cleaned using a sonic bath. Any differences between the two batches should indicate whether the cleaning process has effectively removed contaminants. All chips were dried at 40°C for 18-24 hours.

4) The dried chips were crushed in an agate teema mill to reduce contamination during the sample preparation process. The resultant powders were split and prepared for trace element (pressed pellets) and major element (glass discs) analysis via XRF.

Following the return of the pressed pellets from XRF analysis, another visual inspection for colour will be taken using a 'Munsell Colour Chart'. This will be undertaken on the pressed pellets as these are a uniform grain size for each sample, so colour can be assessed fairly. This secondary visual analysis will add to the data already collected in discerning the separation of flows.

3.2.1. Quality Control

As well as the check on cleaning procedure (mentioned above) other controls on the quality of data have been carried out to ensure results and interpretations made are valid. For the casting of glass discs for major element XRF, 'loss on ignition' (LOI) experiments were conducted (A2). One sample was seen to increase in weight after an extended period of ignition. Whilst unusual this cannot be unexpected. The control taken was to re-run the LOI for this particular sample which resulted in a more conventional loss of mass. Other quality controls were simple but effective measures of keeping samples separated, to avoid cross contamination, and to clean equipment thoroughly after every use.

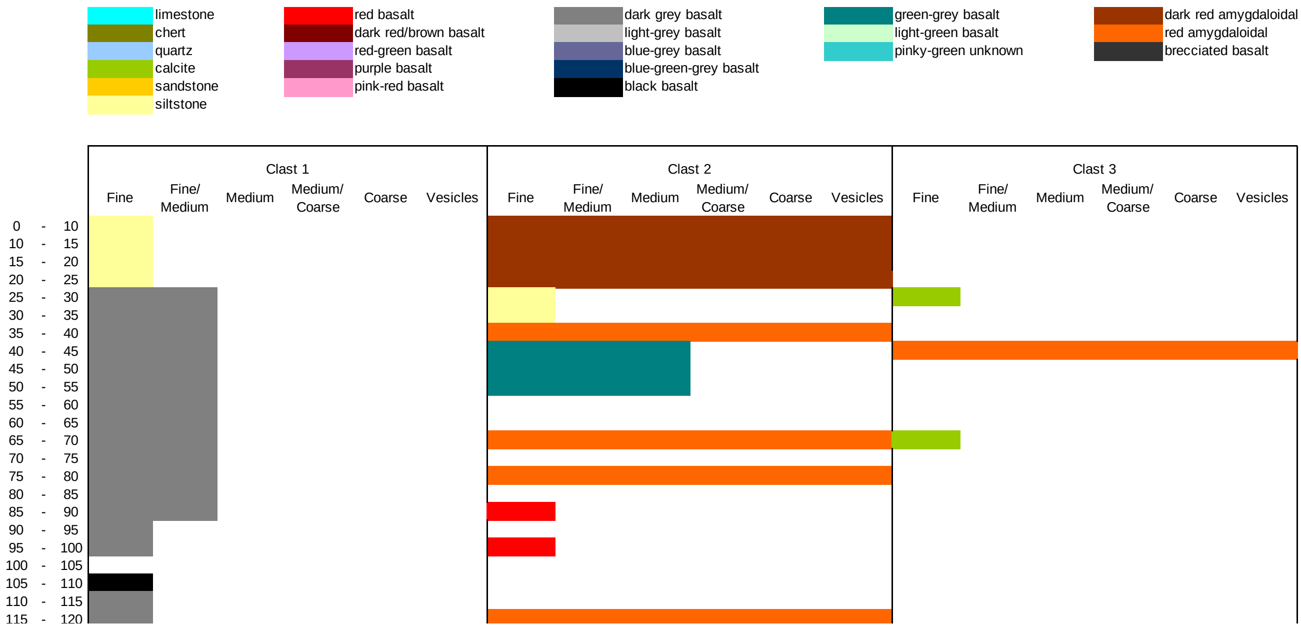


Figure 8: *Representation of the methodology used to convert notational records to a visual representation, distinguishing between lithology, colour texture and grain size. The three most abundant clasts were recorded, accounting for at least 99% of a sample. Vesicles were used as a defining feature of a flow top and thus are made obvious by orange/red bands. See appendix (A1) for full records.*

3.3. Preliminary Results

3.3.1. Visual Analysis

Visual analysis was conducted on all 3 boreholes, generating a crude, simplistic stratigraphy, with definition between sediments, flow top and flow core (fig. 9) Observations have then been compared against those made at the time of logging (Bultitide, 1971). It is assumed that each 'top' and 'core' form a 'single flow unit'. This distinction between flows forms the main hypothesis to be tested by further geochemical analysis - does an individual flow display a distinct geochemical signature, and can this be tracked through the stratigraphy of all three boreholes?

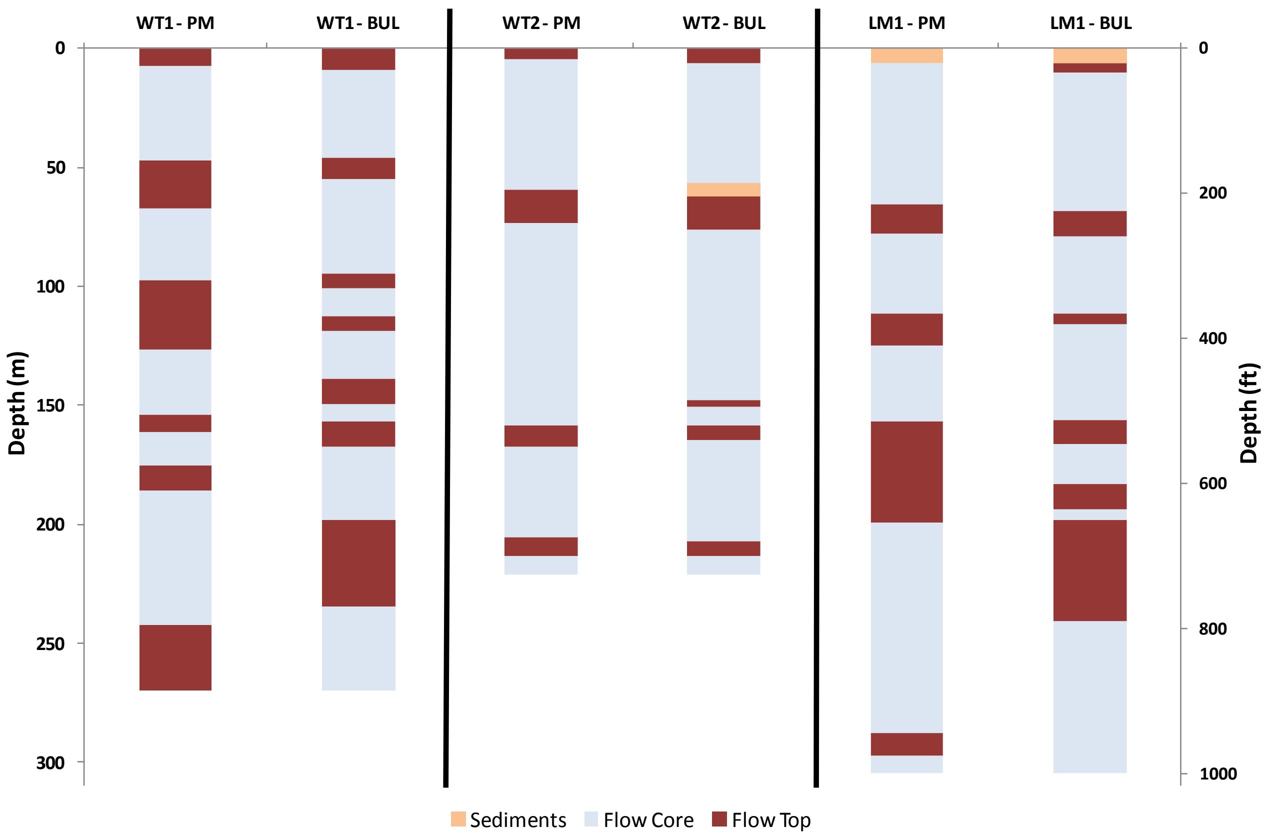


Figure 9: *Graphical representation of volcanostratigraphy for all three boreholes from observational data only (PM), compared against the observations recorded at time of logging (BUL) by R.J Bultitude (1971). See appendix (A1) for enlarged version.*

BMR Waterloo 1 (WT1)

Location: 16°31'7.06" S, 129°5'20.65"E

Total Depth: 269.75 m (885 ft)

Drilling completed: 22/06/70

Analysis:

PM - This hole contains six separate flow tops and 5 complete flow units identified. The thinnest flow measures 21.5 m. The thickest flow measures 67 m with an average flow thickness of 45 m. The lowermost flow contains only flow top, and is truncated by the base of the hole, this is not a complete flow unit.

BUL - Seven different flow units were identified at an average thickness of 38.5 m, the thickest measures 71.5 m thick at least, due to being located at the base of this hole, where it is truncated and thus not a true thickness.

BMR Waterloo 2 (WT2)

Location: 16°24'58.37" S, 129°24'33.27"E

Total Depth: 221 m (725 ft)

Drilling completed: 28/06/70

Analysis:

PM - Four individual flows were identified with an average thickness of 55.25 m. The thinnest flow measures 15 m but this is truncated by the base of the hole and cannot be taken to be a true thickness. The thickest flow measures 99 m, with a flow core of 84 m.

BUL - Five separate flow units identified with an average thickness of 43 m. The thickest flow measures 85 m. The lowermost flow is truncated by the base of the hole, and thus cannot be taken as true thickness. A layer of friable quartz-sandstone is noted at ~55 - 60 m.

BMR Limbunya 1 (LM1)

Location: 17°24'59.79" S, 129°22'38.64"E

Total Depth: 304.8 m (1000 ft)

Drilling completed: 08/07/70

Analysis:

PM - Five separate flows are seen, but only 4 flow tops. The uppermost flow does not possess a flow top, and is overlain by 6 m of limestone. The thickest flow measures 131 m with a 42 m flow top. The lowermost flow is truncated by the base of the hole, its thickness cannot be considered true. The average flow thickness is 59.75 m.

BUL - Topped by 6 m of limestone, this hole contains 6 complete flow units with an average thickness of 49.75 m. The thickest flow measures at least 106.5 m, but is truncated by the base of the flow and so it's true thickness is unknown. The flow top for this unit measures 42.6 m.

3.3.2. Geochemical Analysis

Following on from the visual analysis, directed sampling of all 3 boreholes led to samples being selected roughly every 10 - 20 ft throughout the holes to give a representation of stratigraphy through geochemistry. This will mean a total of 135 samples will be analysed for basic major and trace elements via XRF and ICP-MS. These break down as BMR Limbunya 1 (53 samples), BMR Waterloo 1 (49), BMR Waterloo 2 (33).

Initially 24 samples were chosen from BMR Waterloo 1 and analysed via ICP-MS by Queensland University of Technology (QUT). The resultant data is displayed in A2. Using a TAS diagram the basalt lava flows analysed can more specifically be described as a basaltic andesite or a basaltic trachy-andesite (fig. 10). Figure 11 shows these basalts splitting into 2 groups, one displaying a strong tholeiitic trend, and the other cluster following a calc-alkaline trend.

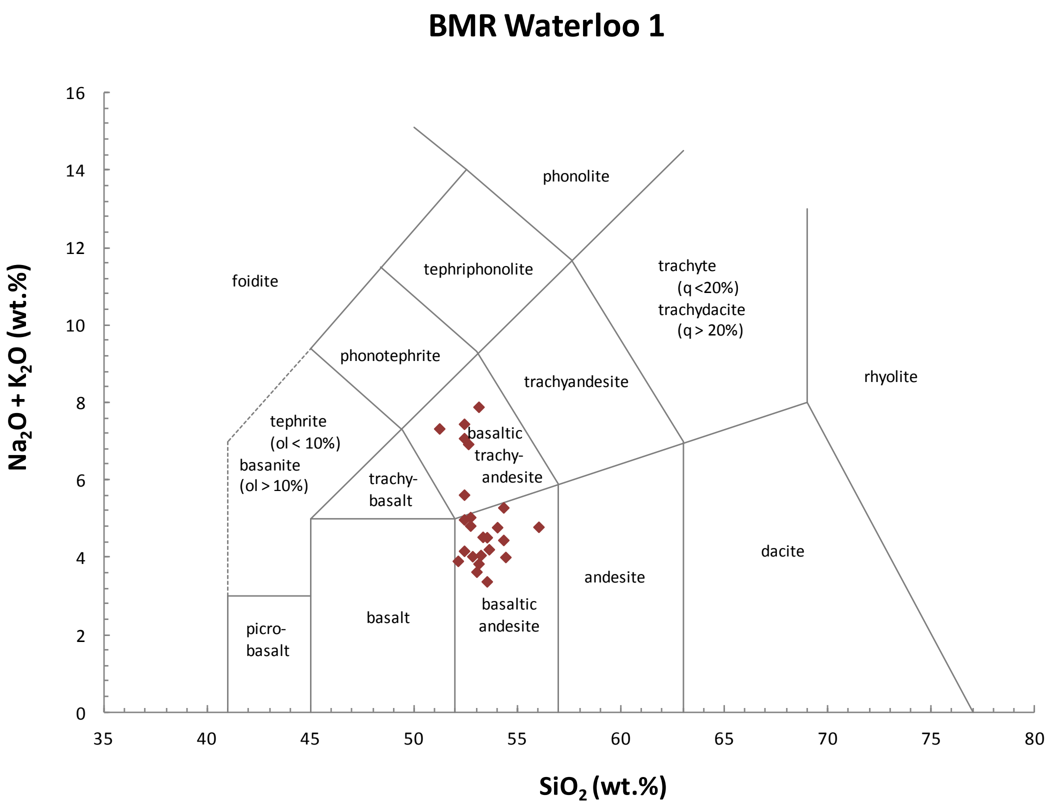


Figure 10: *TAS diagram displaying the IUGS classification of the igneous rocks in BMR Waterloo 1. The majority of lava plots as basaltic andesite, with some plotting as basaltic trachy-andesite due to increased alkali content.*

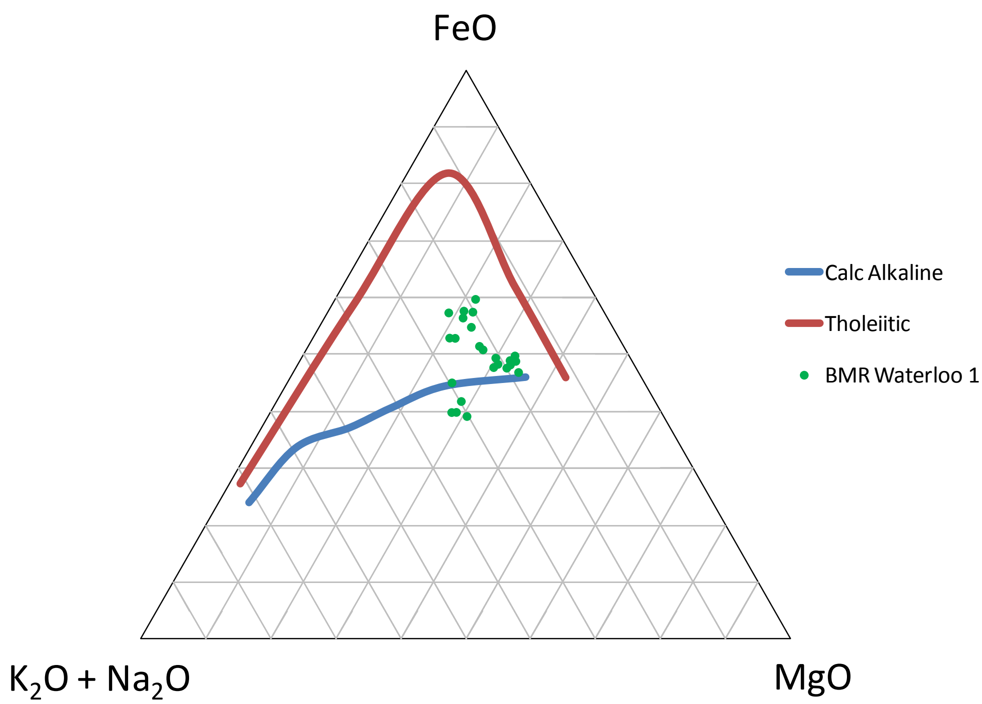


Figure 11: *AFM diagram displaying the split trends within the basalt flows of BMR Waterloo 1. The majority show a strong correlation with a tholeiitic trend, yet a small cluster display a trend similar to calc-alkaline basalt.*

To separate the samples out into distinct flow units, they are plotted in stratigraphic order on a Ni-Cr graph. As figure 12 shows the stratigraphy is split into 6 separate flows by the grouping of adjacent stratigraphic samples. Two flows, one at the top and the other at the base of the stratigraphy plot in the same group. These groups are chemically similar, yet with ~650 ft of intervening material, they are distinguished as separate flows. It is also noted that the plot displays a strong positive trend with all samples plotting close to a straight line. From this analysis, a comparison is drawn with the previous visual analysis to determine further sampling within this borehole (fig. 13).

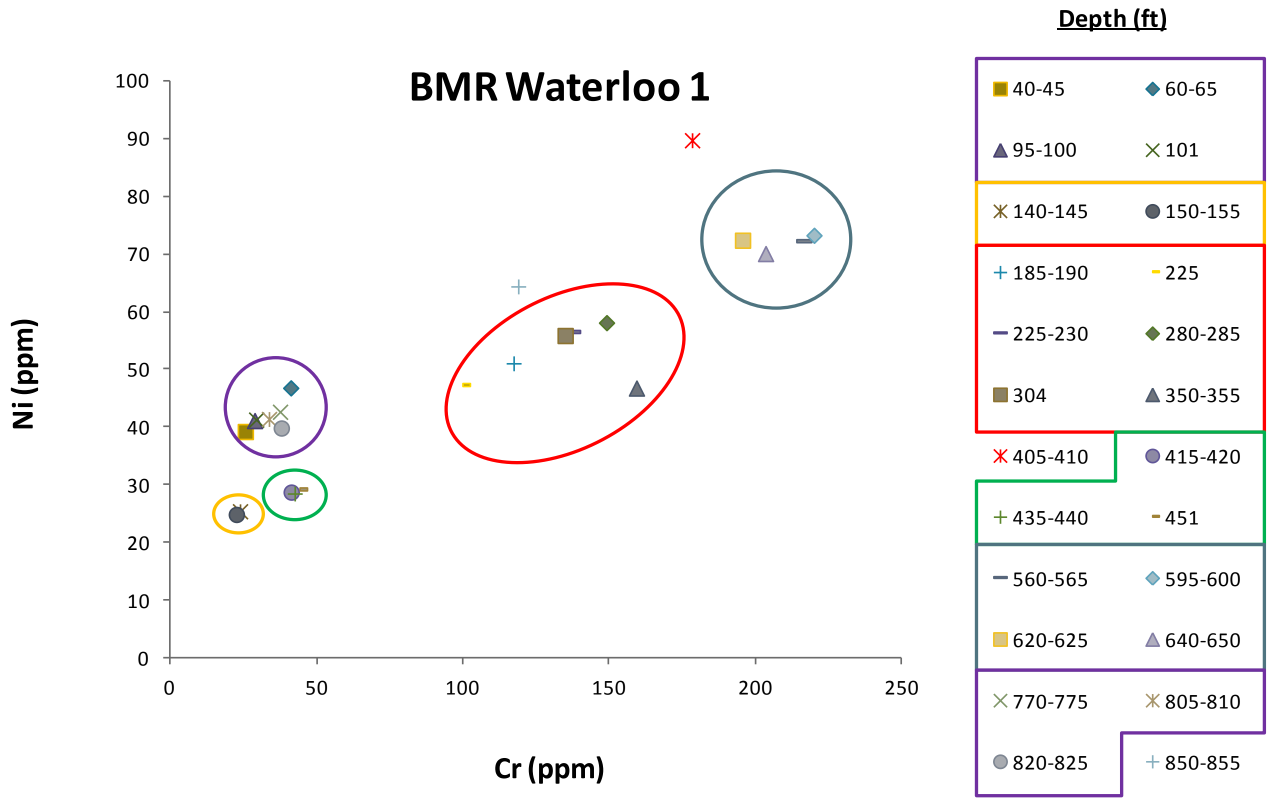
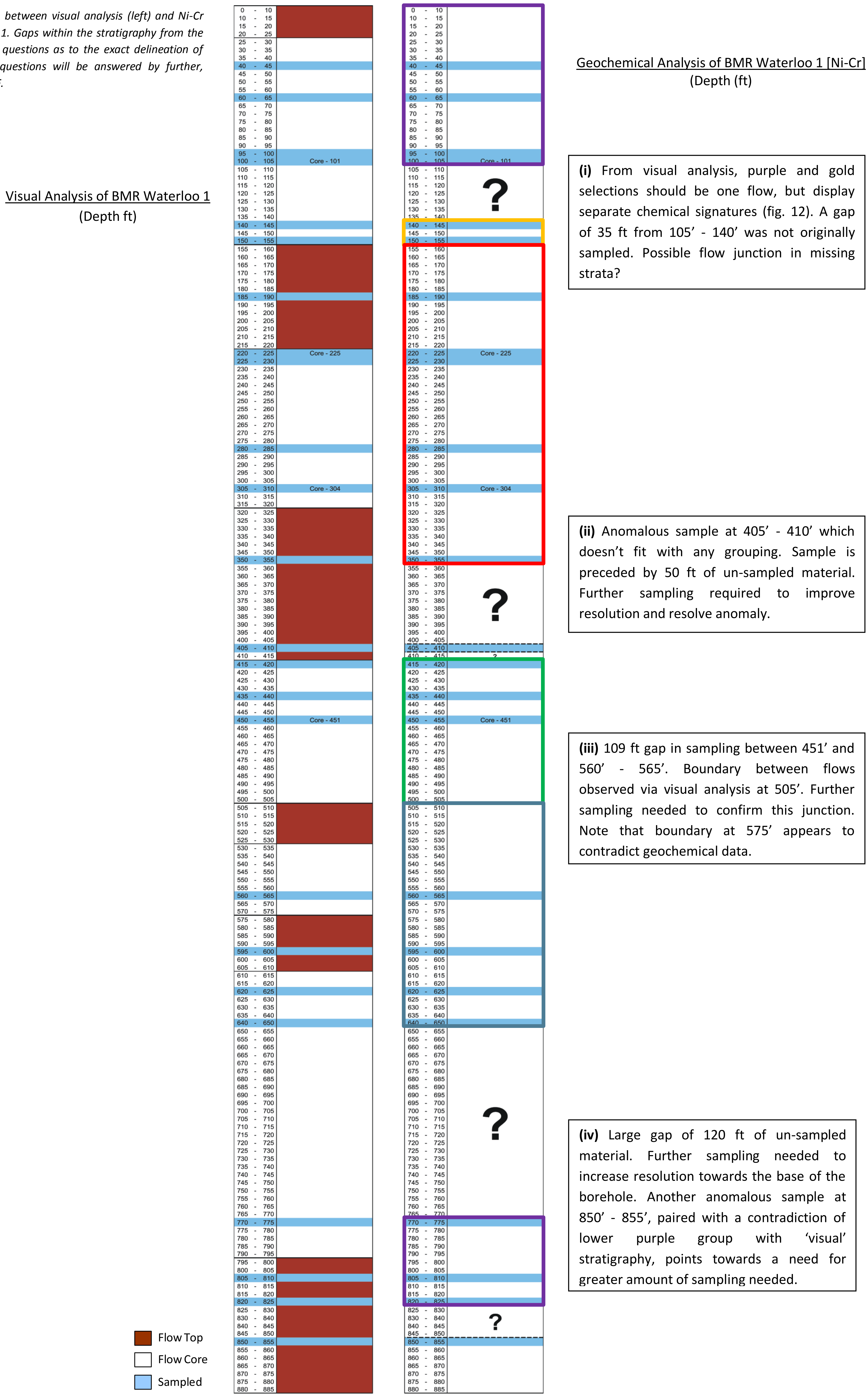


Figure 12: *Ni-Cr plot of samples from Waterloo 1. Different flow units are defined by the groupings shown by different colours. Note the purple group contains samples from top and bottom of the borehole, indicating a chemical similarity, yet they are separated by ~200m of stratigraphy, and as such are different flows.*

Figure 13: *A comparison between visual analysis (left) and Ni-Cr (right) of BMR Waterloo 1. Gaps within the stratigraphy from the Ni-Cr plot (fig. 12) leave questions as to the exact delineation of flow separation. These questions will be answered by further, directed sampling via XRF.*



3.4. Preliminary Conclusions

This study has so far concluded that it is possible to assess volcanostratigraphy through the analysis of rock chips. By employing a unique 3 pronged methodology to analysing the material, interpretations can be drawn together to support one another and give a coherent picture of stratigraphy. As figure 13 shows, the current data provided by QUT are not sufficient to create a comprehensive stratigraphy. However, initial conclusions indicate that while data from visual analysis and geochemical data do not match exactly, 6 separate flows are identified in both, yet gaps in stratigraphy leave questions over flow junction delineation unanswered. Further sampling of BMR Waterloo 1 will increase resolution and answer the questions raised.

Comparisons with observations recorded by Bultitude (1971) give mixed results. BMR Waterloo 2 is logged with extreme similarity by both assessors. BMR Waterloo 2 and BMR Limbunya 1 show large amounts of disagreement, with only a few stratigraphic boundaries being comparable. Closer inspection may be needed on both these boreholes, to re-evaluate how stratigraphy is defined. One point of contention may be the issue of vesiculation and the assumption that this indicates a way-up structure.

Overall the samples analysed display a tholeiitic basaltic andesite signature, agreeing with previous studies (Clark, 2011; Murphy & Widdowson, 2011). Higher Si values, associated with the presence of clay minerals, indicate large amounts of weathering have affected the lava since it was first erupted ~505 Ma. This is not unexpected due to the samples being taken from shallow surface boreholes, which have been sat on a tectonically inactive craton since eruption, allowing for the intrusion of groundwater over time, and thus the subsequent breakdown of primary minerals to clay.

4. Summary

While previous studies of the Kalkarindji have focused mainly on regional scale chemistry (Glass, 2002; Evins et al, 2009), and dating the province as a whole (Hanley and Wingate, 2000; Glass, 2002; Evins et al, 2009), this project aims to define a volcanic stratigraphy within the central zone of the Antrim Plateau through correlation of stratigraphy via geochemistry, geochronology and palaeomagnetism. This study, should give a more comprehensive picture of just how, where and when this ancient flood basalt was erupted onto the Earth's surface.

In respect to answering the four main aims of this project, so far the work has only just begun. The majority of the project is based upon field reconnaissance, which was suspended from November 2011 due to poor weather conditions; it is rescheduled for the 2012 winter dry season. The inclusion of borehole data has, in lieu of field data, gone some way to achieving an aim of setting out a stratigraphy for the Central Kalkarindji region. It has also opened up another dimension to the previous surface exposure work undertaken by Glass (2002) and Clark (2011). By being able to access stratigraphy 300m below the current surface, allows for greater chance of correlation between units.

5. Acknowledgements & References

Thanks to Geoscience Australia for allowing access to the BMR archives in Canberra. Also to N. Clark and B. Gray for assistance in data collection, and N. Clark for providing and explaining the data taken from his study of the volcanic architecture of Blackfellow Creek, 2011.

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Appendix 1

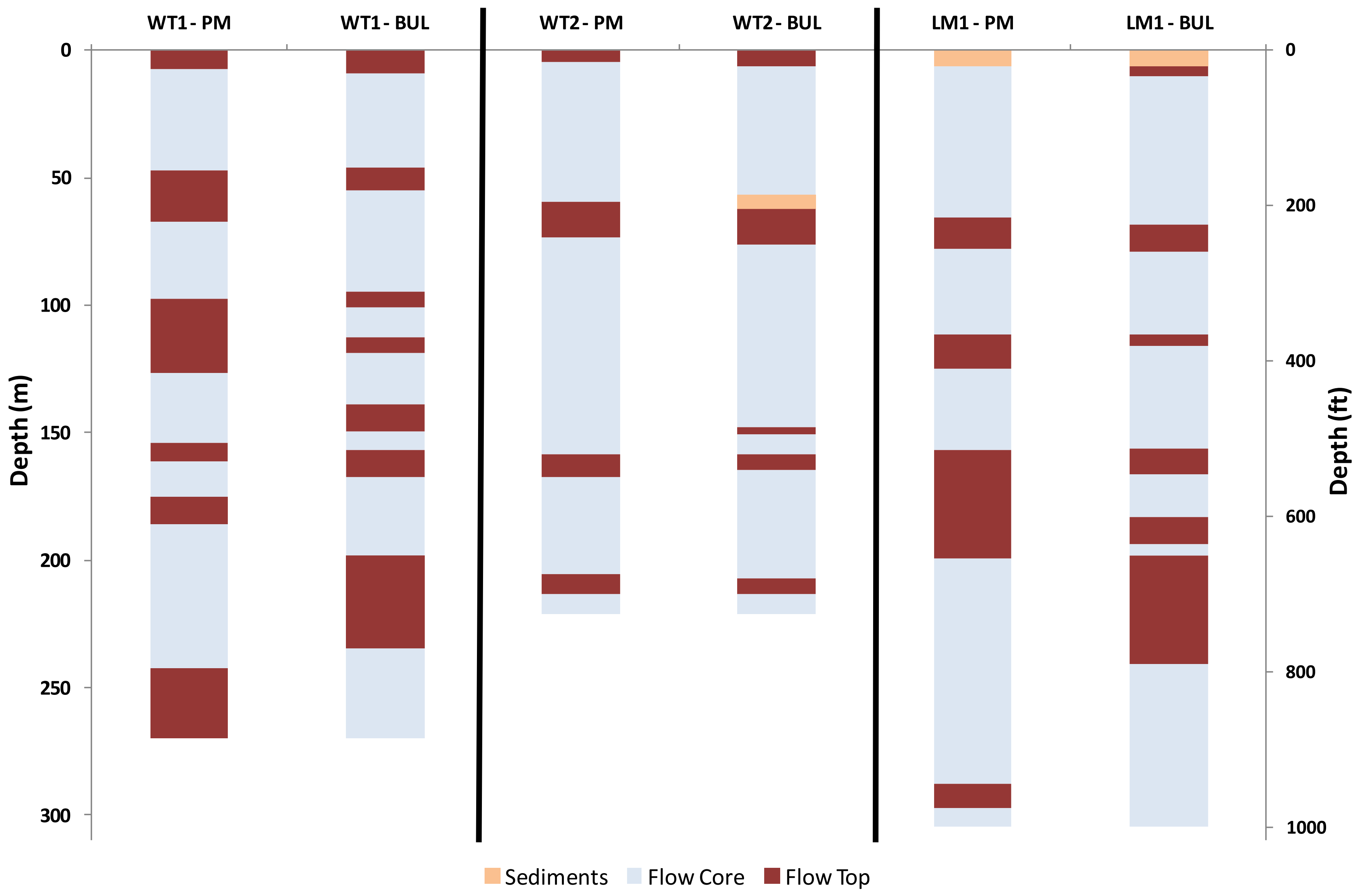
Appendix 2

Major and Trace Element Data of BMR Waterloo 1

Analysed for Queensland University of Technology (QUT)

14/10/2011

SAMPLE	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	K_2O	Na_2O	P_2O_5	BaO	Cr_2O_3	SrO	Total (%)	LOI
40-45	52.70	1.16	14.20	12.15	0.15	5.21	8.18	1.64	3.18	0.12	0.03	<0.01	0.03	**99.98**	1.16
60-65	51.20	1.03	14.00	11.15	0.15	6.29	5.42	2.79	4.54	0.10	0.03	0.01	0.02	**96.86**	
95-100	52.70	1.09	14.30	11.70	0.18	6.01	8.06	1.70	3.34	0.10	0.03	<0.01	0.03	**99.36**	
101	52.40	1.12	14.00	11.55	0.20	6.20	7.94	1.69	3.29	0.11	0.03	<0.01	0.02	**99.94**	1.30
140-145	54.40	1.35	14.20	12.85	0.16	4.67	8.24	1.52	2.49	0.14	0.03	0.01	0.02	**100.15**	
150-155	54.00	1.28	13.75	12.15	0.15	4.61	8.02	1.52	3.26	0.14	0.03	<0.01	0.02	**100.05**	1.01
185-190	52.40	0.83	14.50	9.42	0.16	6.78	5.88	3.42	4.03	0.09	0.03	0.01	0.02	**100.00**	2.38
225	53.50	0.93	14.95	9.88	0.15	6.31	8.89	1.76	2.76	0.10	0.03	0.01	0.02	**99.43**	
225-230	53.10	0.92	14.70	10.05	0.16	6.65	9.60	1.39	2.45	0.10	0.03	0.02	0.02	**100.00**	0.74
280-285	53.00	0.94	14.80	9.91	0.16	6.77	10.10	1.30	2.33	0.10	0.03	0.02	0.02	**100.00**	0.47
304	52.40	0.85	14.95	9.64	0.12	6.16	9.82	1.22	2.95	0.10	0.03	0.02	0.02	**99.99**	1.63
350-355	52.80	0.90	14.90	10.20	0.13	6.95	9.20	1.40	2.63	0.10	0.03	0.02	0.02	**99.39**	
405-410	52.10	0.90	14.40	9.94	0.15	7.37	8.28	0.98	2.93	0.10	0.03	0.02	0.03	**100.00**	2.63
415-420	52.40	1.39	13.50	13.45	0.18	4.40	6.99	2.73	2.89	0.14	0.04	<0.01	0.03	**99.99**	1.74
435-440	54.30	1.38	13.80	11.95	0.17	4.34	8.31	1.74	2.71	0.14	0.03	<0.01	0.02	**99.97**	0.99
451	53.30	1.36	13.75	12.90	0.15	5.03	7.59	1.72	2.81	0.14	0.03	<0.01	0.02	**98.93**	
560-565	52.40	0.81	14.90	9.16	0.14	7.18	5.52	2.85	4.23	0.09	0.03	0.03	0.02	**97.46**	
595-600	53.20	0.89	15.25	9.73	0.14	6.65	9.11	1.51	2.55	0.10	0.03	0.03	0.02	**99.99**	0.70
620-625	53.60	0.91	15.05	10.05	0.15	6.10	8.68	1.67	2.54	0.10	0.03	0.02	0.02	**99.01**	
640-650	52.60	0.84	15.00	9.71	0.15	6.62	5.39	2.21	4.72	0.09	0.04	0.04	0.03	**97.48**	
770-775	53.10	1.36	14.95	9.74	0.09	6.84	3.06	1.78	6.11	0.15	0.03	<0.01	0.02	**100.00**	2.68
805-810	54.30	1.26	14.30	10.75	0.17	4.29	8.58	1.42	3.87	0.14	0.03	<0.01	0.02	**99.98**	0.77
820-825	56.00	1.14	14.60	10.05	0.13	4.18	7.86	1.85	2.94	0.13	0.04	0.02	0.03	**99.03**	
850-855	53.50	0.94	15.15	9.59	0.13	6.31	10.10	1.06	2.32	0.10	0.03	0.02	0.02	**99.31**	


WT1 - PM
WT1 - BUL
WT2 - PM
WT2 - BUL
LM1 - PM
LM1 - BUL
0
50
100
150
200
250
300
Depth (m)
0
200
400
600
800
1000
Depth (ft)
Sediments
Flow Core
Flow Top