The Kalkarindji Flood Basalt Province of Australia: comparisons with the Siberian Traps CFBP and associated Noril'sk Ni-Cu-PGE mineralization

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Part 1

Overview – The Geological Context of Continental Flood Basalts

Continental Flood basalt provinces (CFBPs) are an important member of a family of major eruptive suites known as Large Igneous Provinces (LIPs). CFBPs are characterised by dominantly basaltic volcanic products (typically lava flows) erupted into sub-aerial continental environments. The emplacement of a CFBP on a continent, or along a rifting continental margin, is an event of major regional and sometimes global significance. In order to understand the mantle processes responsible for the genesis of CFBPs and the resulting volcanic products, it is important to interpret the igneous record jointly with other observations. Besides the volume, age and composition of the igneous rocks themselves, the inter-relationships between sedimentation or erosion, tectonics and magmatism are, in most cases, the only evidence available for constraining the genesis of ancient CFBPs.

There are a number of CFBPs recognized around the globe, among the most significant and widely studied are the Siberian Traps (c. 2 - 3 x 10^6 km^3; 249 - 251 Ma), the Emeishan Traps of SW China (< 0.5 x 10^6 km^3; c. 260 Ma), the Karoo of South Africa (c. 2.5 x 10^6 km^3; c. 183 Ma), the Deccan Traps of India (1.3 x 10^6 km^3; c. 64 - 67 Ma), and the Columbia River Basalts of noth-western USA (< 0.2 x 10^6 km^3; c. 14 -15 Ma). The Kalkarindgi CFBP of Australia is a recently recognized example dated at c. 505 - 508 Ma which, because of its considerable antiquity, now consists only of a scattered series of basaltic suites that occur across northern and central Australia; its original size is estimated as significantly exceeding 5 x10^5 km^3 (Glass and Phillips, 2006).

The defining characteristic of CFBP formation is the geologically rapid eruption (within a few million years) of unusually large volumes of magma, mainly silica-saturated basalt or tholeiite. It is usually accepted that rapid and voluminous melt generation requires decompressional melting of the upper mantle. Decompression is an efficient mechanism for generating large amounts of melt because the adiabatic temperature gradient (about 0.6 °C/km; (McKenzie and Bickle, 1988) is much steeper than the gradient of the solidus both for anhydrous mantle peridotite (about 4–5 °C/km at lithospheric depths) and for more enriched mantle compositions. Upwelling of mantle to cause decompressional melting can be active, driven by buoyancy forces that set up a convective circulation, or passive, in response to thinning of the lithosphere. There are two families of models for active upwelling. In one family, convection is controlled by lateral density variations related to heating within the mantle (often described as ‘mantle plume’ models), whereas in the other, convection is controlled mainly by lateral density variations related to cooling of the plates (often described as top-down convection models). It is also important to consider how the overlying lithosphere deflects in response to such mantle convection. One common response to this mantle upwelling is a thinning of the overlying lithosphere which, under a broad regional extensional regime, can result in lithospheric extension and continental rifting. Accordingly, many CFBPs are associated with rifted continental margins.

One explanation of the formation of LIPs (and hence CFBPs) is that they represent an anomalous transient period of high plume flux, perhaps associated with an initiating, or ‘start-up’ plume. The predicted shape and rise time of start-up plumes are strongly dependent on assumptions about mantle viscosity structure, rheology and the relative importance of internal and basal heating. In a Newtonian, isoviscous fluid with all buoyancy supplied from below, starting plumes form roughly spherical diapirs (Campbell and Griffiths, 1990; Griffiths and Campbell, 1991; Richards et al., 1989). When this model is applied to explain LIPs, the diapir (or plume head) needs to be initially about 1000 km in diameter and, upon impact with the base of the lithosphere, the head is predicted to spread laterally to form a sub-lithospheric structure some 2000 km in diameter. However, the viscosity in the mantle probably decreases by several orders of magnitude from bottom to top. In this case, diapiric plume heads are predicted to narrow and rise more rapidly towards the top of the mantle (Farnetani and Richards, 1994). If the mantle rheology is strongly non-linear, then start-up plume heads are predicted to be only a few hundred km in diameter, similar to the diameter of the trailing plume conduits (Larsen et al., 1999). These dynamics are of importance when considering the region of the lithosphere (including the continental crust) likely to have been directly affected by both intrusive and extrusive volcanism.

The Kalkarindji CFBP, Australia

The Antrim Plateau Volcanics, Northern Territory and West Australia are a component of the larger Kalkarindji Large Igneous Province (LIP) that extruded in the Early Cambrian (ca 508 Ma; (Glass and Phillips, 2006). The province formed when Northern Australia formed the western margin of the Gondwana super-continent (Torsvik et al., 2008b). The original extent of extruded basalt is unknown but may have been > 2.1×10^6 km^2, making the Kalkarindji province one of the largest LIPs of the Phanerozoic (Evins et al., 2009).

The regional geochemical study of the Antrim Plateau Volcanics of (Glass, 2002) demonstrated that these basalts typically represent shallow mantle derived low-Ti tholeiitic melts that have undergone significant crustal contamination and crystal fractionation (Glass and Phillips, 2006). The chemical similarity of the Antrim Plateau Volcanics to the Nadezhdinsky formation of the Siberian Traps, which are genetically associated with the Noril'sk Ni-Cu-PGE deposits, makes the Kalkarindji province a prime target for Ni-Cu-PGE exploration.

The Noril'sk Ni-Cu-PGE deposits are associated with major crustal faults that acted as conduits for lavas and allow for the formation of large-scale shallow magma chambers in which Ni-Cu-PGE deposits form. These magma chambers are thought to have formed beneath the vent systems. Similarly, the Kalkarindji province is cut by large scale crustal faults; examples include Halls Creek Fault system including the Neave Fault, Black Fellow Creek Fault and the Baines Fault in the Northern Territory. However, presently no shallow magma chambers associated with the Kalkarindji province have yet been identified through geophysical surveying in the vicinity of these faults.

Tectonic setting of the Kalkarindji CFBP eruptions

In order to determine the broader structure of any CFBP, the spatial distribution and thickness of the constituent lava successions, and the likely geographical position and distribution of crustal magma chambers, dyke conduits, and vent sources, it is first necessary to place the CFBP within its tectonic setting. This necessity arises because of the close association between continental rifting events, and CFBP magmatism. The Kalkarindji CFBP was erupted upon the Australian craton in the early Phanerozoic (mid-Cambrian), but the tectonic setting of this cratonic region has its origins in the palaeogeographic continental distributions of the Precambrian - in the latest part of the Neoproterozoic (c. 700 to 542 Ma). Such reconstructions rely upon paleomagnetic data, but there is a paucity of such information from the latest Mesoproterozoic through Neoproterozoic time.

Since the early 1990s, Precambrian paleogeographic reconstructions have consistently incorporated a vaguely resolved Neoproterozoic supercontinent, named Rodinia (Hoffman, 1991; Torsvik et al., 1996). This is postulated to have amalgamated about 1.0 Ga and to have disintegrated at around 850-800 Ma (Torsvik, 2003). In Rodinia times, Western Australia (WAUS) and eastern Antarctica (EANT) were linked, and their calculated position predicts that this WAUS-EANT part of the Rodinia landmass were together located at tropical to subtropical southerly latitudes from ca. 1 Ga to 420 Ma. (Torsvik et al., 2008a). The subsequent breakup of Rodinia resulted in the formation of another supercontinent, Gondwana, at ~550 Ma. Gondwana incorporated all of Africa, Madagascar, Seychelles, Arabia, India and EANT, and most of South America and Australia.

This association of major continental rifting events with flood basalt volcanism is well recognized throughout Phanerozoic history, and the protracted break-up of Gondwana is intimately associated with CFBP events. For instance, the separation of South Africa from western Antarctica (Dronning Maud Land) at c. 180 ma resulted in the Karoo CFBP (South Africa), and associated Ferrar volcanic province (Antractica). During the mid-Cretaceous (c. 130 Ma) seafloor spreading propagated between EANT and India and, at the same time, India broke off from Australia forming ocean basins west of Australia (Perth, Cuvier, and Gascoyne abyssal plains). The opening of Southern Ocean between southern Australia and EANT did not occur until c. 50 Ma. Importantly, all of these rifting events substantially post-date the Kalkarindji CFBP. Accordingly, if this Cambrian CFBP was associated with a rifting event, it must have occurred to the NW of Australia since the continental areas to the west and south of WAUS did not separate until much later.

Whilst it would be entirely consistent to assume that the Kalkarindgi CFBP is associated with a major continental extension/rifting event at c. 510Ma, the palaeomagnetic reconstructions indicate this to be a period dominated by the assembly of Gondwana, and one characterised collisional rather than extensional (i.e. contintal rifting) tectonism. In this tectonic context, the origin of the Kalkaraindji CFBP remains enigmatic.

Noril’sk-type Cu-Ni deposits and the Siberian Traps CFBP

The Noril’sk area of Siberia hosts the mineral deposits of Noril’sk -Talnakh which are currently the largest known nickel-copper-palladium (Ni – Cu – Pd) deposits in the world. The companies based in the region are the world's leading producers of nickel and palladium, and also produce significant quantities of in platinum, copper and cobalt (Pt, Cu, Co). It is ranked among the top four world platinum producers.

The Noril’sk -Talnakh nickel-copper deposit was formed 250 million years ago during the eruption of the Siberian Traps igneous province. An estimated 3 -4 million cubic kilometres of lava were erupted, a large portion of which was expelled through a series of flat-lying lava conduits lying below Noril’sk and the Talnakh Mountains. The gases released from Siberian Traps are considered to be responsible for the global mass extinction event at the end of the Permian period (c. 250 Ma). The ore was formed when the erupting magma encountered significant thicknesses of organic-rich sediment during its ascent and eruption. As a result, the magma became comtaminated with elements that had been sequestered during the deposition of these earlier organic-rich rocks, effectively becoming saturated in sulphur, and forming globules of pentlandite, chalcopyrite, and other sulphides. Once formed, these molten sulphides were themselves able to sequester trace elements which are otherwise relatively incompatible in basaltic magmas (i.e. chalophile elements) during their passage through the crustal conduits. In effect, the sulphide phases became continually enriched in a range of commercially important elements as the lavas passed surface ward. Given the huge volumes of lavas that passed through these sulphur-bearing conduits, the trace element concentration hosted in these sulphides became hugely upgraded with nickel, copper, platinum, and palladium. Once the magma supply from partial melting of the mantle ceased (i.e, the ‘plume head’ had become exhausted), the sulphur-rich materials held and retained within the conduits and magma chambers ‘froze’, thus preserving huge chalcophile enrichments.

The current resource known for these mineralised intrusions exceeds 1.8 billion tons. The ore is currently mined underground via several shafts, and ore deposits are currently being extracted at >1,200 m below ground, since they are hosted in the ‘high-level’ sill-like bodies which were the magma chambers that froze within the upper part of the continental crust. These sub-surface deposits are typically identified and explored using electromagnetic field geophysics, with detection loops on the Earth's surface with dimensions of over 1,000 m on a side. Such apparatus is able to image the conductive nickel ore at depths in excess of 1,800 m.

Part 2

Geological mapping of Kalkarindji Basalts in the vicinity of the Black Fellow Creek Fault, Waterloo, Northern Territory

A series of target areas were identified using a combination of existing survey data, borehole data, and satellite imagery. These were then investigated in detail through targeted field work during October and November 2010.

Purpose of the Field Trip

On satellite imagery, a dark coloured oblate feature that defines a horseshoe-shaped set of hills is clearly observable on Google images near the northern termination of the Black Fellow Creek Fault, Waterloo, Northern Territory. This feature is associated with a minor magnetic anomaly (Stockdale Prospecting Ltd, 1998) and has been postulated to be an erosionally-exhumed portion of an intrusive body; accordingly it was the main focus of this study. It represents an obvious target for geological mapping to:

1. Ascertain whether or not the dark coloured oblate feature represents an intrusive body;
2. Conduct a detailed investigation of the stratigraphy of the basalt flows in the area to characterise the nature of the volcanism, and extent of individual eruptive units.
3. Evaluate whether the volcanic succession preserved in the vicinity of the Black Fellow Creek Fault formed proximal to a vent source.
4. Ascertain whether flow-direction indicators are preserved in the basalt lava units, and if so, use these to better constrain the sites of source vents or feeder-dyke complexes.
5. Determine whether there is evidence of movement on the Black Fellow Creek Fault during, and/or after the emplacement of the basalt succession

Methods

A detailed four week reconnaissance mapping expedition was conducted centred upon the dark-coloured oblate feature near the northern termination of the Blackfellow Creek Fault. During this work the dark coloured oblate feature was mapped in detail, the stratigraphy of the basalt flows to the east and to the west of the Black Fellow creek was logged through a series of detailed traverses, and the contact between the basalts and the underlying sediments was observed and logged in one locality.

Results

Dark-coloured oblate outcrop: This feature, which is so striking on Google Earth satellite images (Fig. 1), contains a succession of lava flows that are essentially identical to the surrounding basalt stratigraphy. There is no evidence for an intrusive structure. The only distinguishing feature of the basalts that lie within the boundaries of the dark feature is that they contain trace amounts of pyrite; however, this in itself would not result in their distinctive signature. The reason for their colouration is purely the result of the local topography because here, erosion has eroded the basalt succession to the level of a particularly well-developed brecciated flow top. This brecciated flow top is black on the weathered surface, and offers a litho-type which is unique in texture and composition as compared with adjacent flows, and flow core materials. As a result the area exposing this breccia exhibits a different colour to that of the surrounding area which has eroded to different levels within the basalt pile.

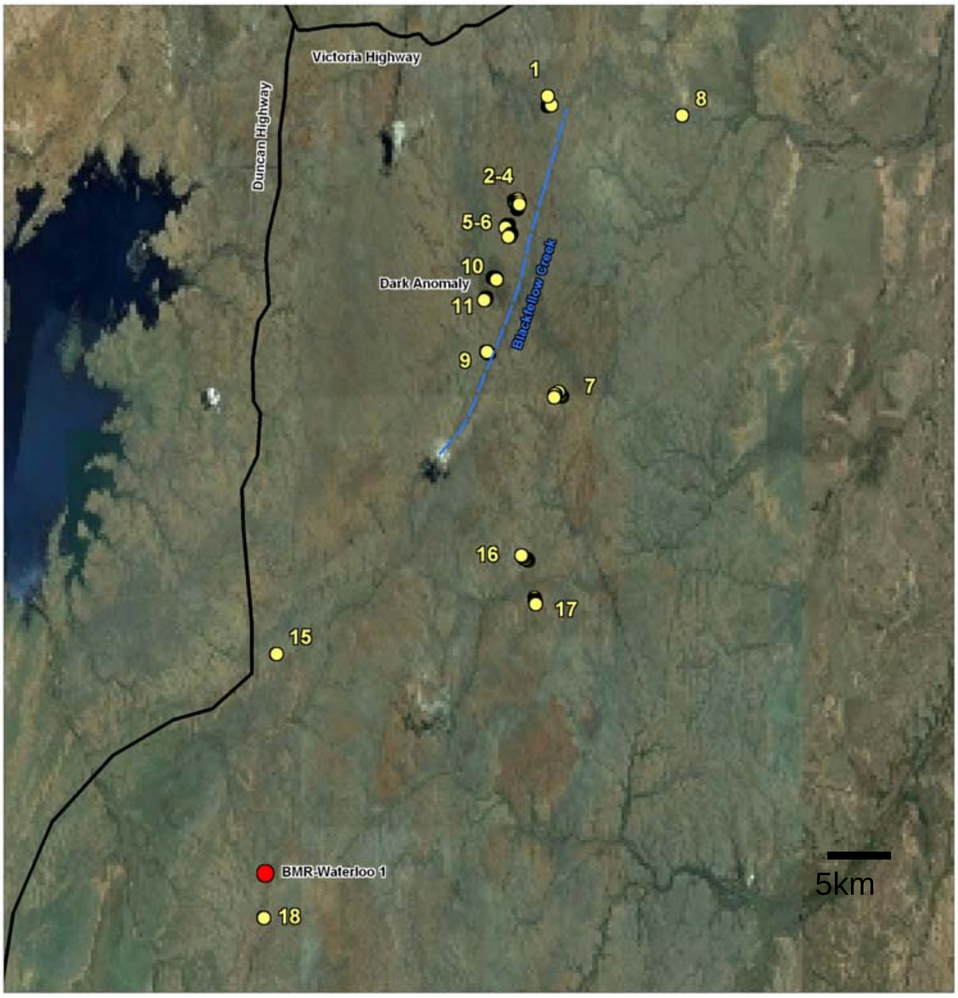

Figure 1: Location maps for the stratigraphic sections in the Waterloo Area. The numbers refer to the stratigraphic traverses given in Table 1 and described in Figure 2.

Table 1. Locations of Stratigraphic Traverses. Stratigraphic numbers are those used in the location map Figure 1.

No. On Key	Stratigraphic Section	Northing	Easting	No. On Key	Stratigraphic Section	Northing	Easting
1	Blackfellow Fault Splay	535006	8220374	10	Eastern Dark Anomaly	529845	8208792
2	Parallel Ridges East 1	532020	8213834	11	Western Dark Anomaly	528599	8207498
3	Parallel Ridges East 2	532150	8213682	12	Dark Anomaly Eastern Transect	528919	8207339
4	Parallel Ridges East 3	532162	8213539	13	Dark Anomaly Western Transect	529103	8207788
5	Parallel Ridges West 1	530731	8212065	14	Dark Anomaly Western Transect 2	528987	8207858
6	Parallel Ridges West 2	531031	8211498	15	Byrnes Hill	507664	8185106
7	Super Hill	535629	8201337	16	In Between Hill	532326	8191329
8	Sedimentary Hill	548553	8219141	17	Microwave Tower	533741	8188254
9	Tablelands	528894	8204212	18	Limestone Hill	506403	8168508

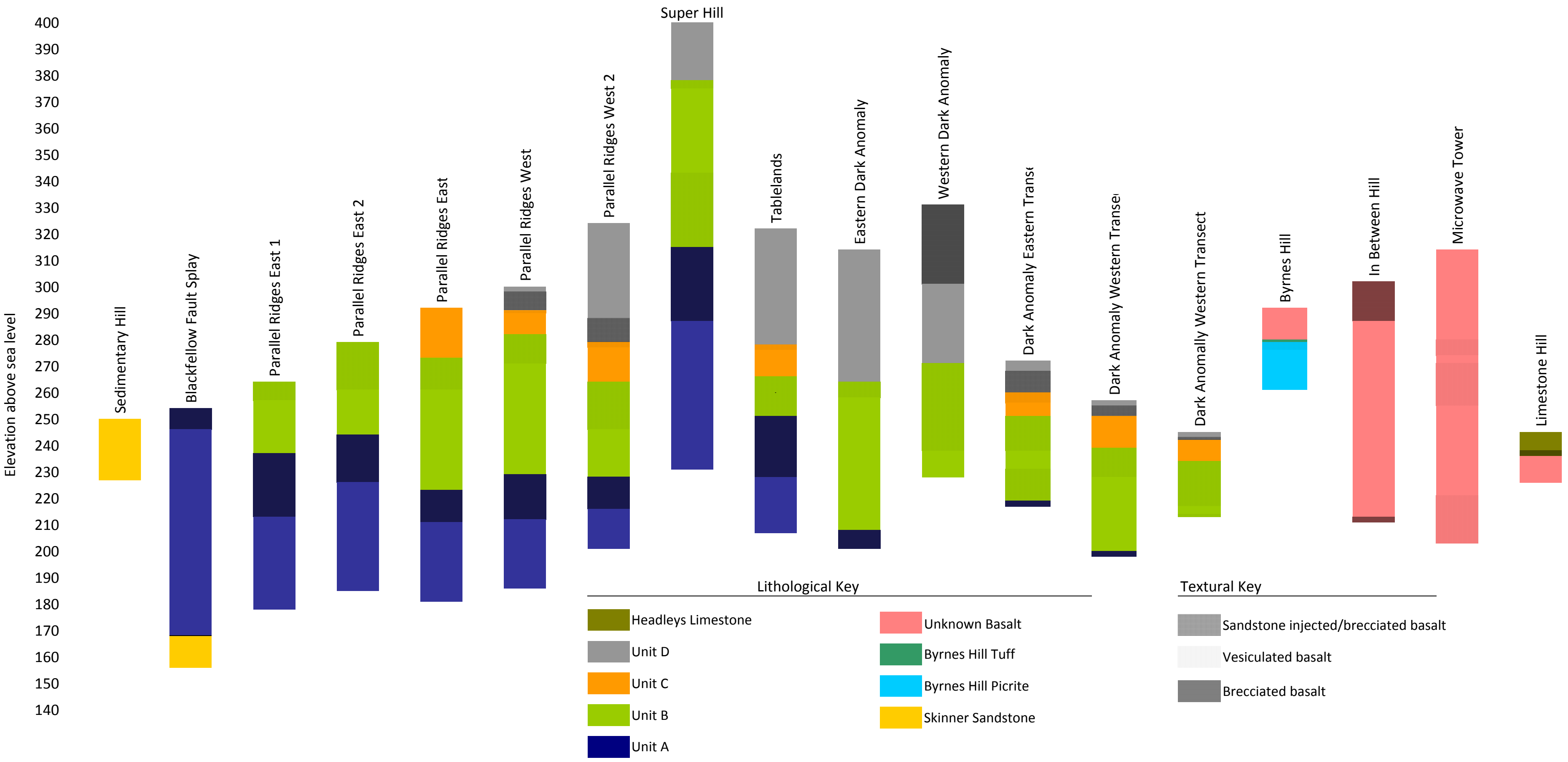

Figure 2: Stragigraphic Traverses for the Waterloo Area. Locations of traverses are given in Figure 1 and Table 1

Basalt Stratigraphy: The stratigraphy of the basalt in the vicinity of the dark-coloured feature is straight forward, and consists of four near flat lying lava units: Units A, B, C & D are discussed below, and are shown in Figure 2. These units are sufficiently distinctive to be correlated with confidence over distances of >10km, and correspond to pahoehoe type inflation units. The base of Unit A was observed in contact with underlying sediments in one locality (Blackfellow Creek Fault Splay Traverse). The three southernmost traverses were the only basalt traverses that did not encounter this distinctive stratigraphy.

Unit A: The basal unit is a very distinctive and unusually thick lava flow that ranges in thickness from 60 to 130m. In detail, the unit usually consists of a 40 to 110m thick basal component of massive fine- to medium-grained basalt containing sparse vesicles indicating it had become effectively degassed on eruption. The unit is cut by a set of columnar cooling joints characterised by slightly curved joint faces and by regional tectonic joint sets. The massive interior of the flow contains rare coarse-grained (i.e. pegmatite-like) segregation veins of predominently plagioclase and augite similar to those described in the Columbia River Basalts (Puffer and Horter, 1993). The upper 15 to 20m of the unit consists of a very thick rubbly flow top breccia. This breccia comprises highly vesicular basaltic clasts set in ash-like matrix cut by injections of fine-grained massive basalt probably sourced as break-outs from liquid flow core, and intruded as small fissures in the lava crust. The rubbly flow top is similar but an order of magnitude thicker than those observed above comparable flows in the Deccan Traps (Duraiswami et al., 2008).

Unit B: This is a relatively typical albeit ~30-70m thick simple lava unit with significant vesiculation at the flow top (~10-15m) and base (up to 5m), and a massive interior.

Unit C: This unit is approximately 10m thick. The unit consists of plagioclase phyric basaltic lava that fractures into very distinctive horizontal plates. At the top of the unit very large vesicles are observed (up to 10cm). The vesicles are commonly elongated in a consistent north-south orientation. This unit was not observed on the Super Hill traverse to the SE of the Black Fellow Creek Fault, though this discontinuity may be a result of poor outcrop of the unit.

Unit D: This unit is at least 50m thick. The unit is commonly observed to sit on a 2 to 3m thick sandstone. The base of the unit is generally brecciated and many of the breccia clasts show quenched rinds. The bulk of the unit consists of massive fine- to very coarse-grained basalt with very rare vesicles. The upper portion of this unit was only observed in 2 localities and was observed to be a >10m thick rubbly flow top breccia similar to Unit A.

To the south at In Between hill, Microwave Tower and Byrnes Hill significantly different basalt stratigraphies are observed with no flow that can be correlated to the northern stratigraphy based on their morphology (Fig.2).

A stratigraphic traverse was conducted on In Between Hill which is located 15km south of the Black Fellow Creek Traverses. This hill consisted of basaltic lava units that, on the basis of observable physical properties alone, could not be readily correlated with those that comprise the northern stratigraphy. The stratigraphy of the hill from bottom to top is:

- The base of the traverse initiated with a fine grained vesiculated lava flow top, the massive component of the unit was not observed.
- The overlying unit was a thick (80m+) flow with a brecciated flow top (15m+). It could not be correlated with other flows although could possibly be a lateral equivalent of Unit A. However this flow had less brecciation on its flow top and far more pegmatitic zones within the massive component of flow. Tectonic jointing is also present of two main orientations (N40W, 90) and (N45E, 90). These joint orientations are quite similar to those observed in Unit A.

A stratigraphic traverse was done on Microwave Tower which is 5km further south from In Between Hill. Again this hill did not contain lava flows that could be correlated with either In Between Hill or the northern stratigraphy.

- The base of the traverse initiated with a fine grained vesiculated lava flow top. The massive component of the unit was not observed.
- Overlying this unit was a thick (~60m) lava flow with a vesiculated flow top (~25m). It is difficult to correlate this with northern flows. It is unlikely to be Unit B as it shows a completely different weathering pattern. The unit contained what was likely a pod of massive fine grained basalt.
- On top of this unit was a third basalt unit with a peculiar layered appearance with some layers appearing to be oxidized. The oxidation was witnessed only towards the base with it disappearing up section as the units grains also coarsened.

Due to time constraints, Byrnes Hill was cursorily mapped without a detailed stratagraphic traverse. Nevertheless, a unique stratigraphy was observed with inter-bedded clean quartz-rich sandstones and relatively thin basalt flows (5-20m) from the base to close to the summit. The basalts commonly show fractures that are infilled with sandstone. Near to the summit, a fine grained light green 30cm thick layer occurs; this is interpreted as a volcanic tuff and overlies what appears to be, based on geochemical work (Glass, 2002), a high Mg basaltic unit. This is then overlain by another a basalt flow.

Discussion:

Proximity to a Vent Source: No definitive evidence for a nearby vent was observed. Pahoehoe inflation units, such as Units A-D, can extend up to 100s of kilometres in continental flood basalt provinces (Self et al., 2008). The very thick nature of Units A-D could reflect topographic ‘ponding’ of the flows in a topographic low rather than reflect proximity to a vent site. Eruptive units of 20 m thickness are commonplace in many CFBPs, whilst units of 50 – 100m are recorded without proximal association to vent sources. Nevertheless it may be possible to use block size distributions within the rubbly flow tops to make some interpretations about the emplacement conditions of the lavas (e.g (Anderson et al., 1998)).

Timing of Movement on the Faults: The Black Fellow Creek fault is a NNE-SSW trending feature that has been interpreted as a splay of the crustal scale Halls Creek Fault and is thought to have been active before, during and after basalt emplacement (Gole, 2009). In this study pre-eruptive movement of the fault was not investigated. Post-eruptive movement of the fault was clearly evident in a highly tectonised outcrop of Unit A in the black Fellow Creek. In order to assess whether or not the black fellow creek fault was active during basalt emplacement stratagraphic traverses where performed on either side of the fault. The stratigraphy is very similar on either side of the fault, however, the units are significantly thicker to the southeast (Fig. 2). In addition a vesicular lava flow top was observed underlying Unit A on the Super Hill Traverse. This contrasts with the sediments that were observed to underlie Unit A in the Black Fellow Fault Splay traverse (Fig. 2). The change in thickness across the fault together with the presence of a lava flow underlying Unit A strongly suggests that the Black Fellow Creek Fault was active during basalt emplacement affecting topography.

The three southern most stratagraphic traverses are significantly to the south of Blackfellow Creek Fault. No Fault is presently mapped in this area, yet here we propose that there must be a significant fault or faults between the Blackfellow Creek Fault and the In Between Hill traverse and between the In Between Hill and Microwave Tower sections because of the significant variation in the stratigraphy between the different traverses. Furthermore the Waterloo Stratagraphic Drill Holes (Fig.1) drilled just to the south of the areas mapped encountered >1km thickness of basalt (Bultitude, 1971). This undoubtedly indicates that faulting has occurred between the Black Fellow Creek traverses and the Waterloo Stratagraphic Drill Holes with at least 1km of vertical movement.

Flow Direction Indicators: Unit C shows clear indicators of flow direction as elongated mega-vesicles in the lava flow top. These vesicles are orientated consistently north-south and are commonly tadpole shaped with their tails to the south. This implies that the lavas have flown from south to north. No other flow indicators were observed in the area.

Part 3

Copper mineralisation in the Headley Limestone, Waterloo, Northern Territory

The Headley Limestone is a component of the Middle Cambrian Tindall Limestone, which is an extensive limestone unit within the Middle Cambrian to Early Ordovician age Daly River Group (Lindsay et al., 2005). These sediments were deposited in a broad shallow intra-cratonic 'sag' that extends across more than 40,000 km^2 of the northern portion of Northern Australia (Lindsay et al., 2005). The Tindall Limestone is typically observed as lying stratigraphically immediately above or upon Palaeoproterozoic rocks of the Antrim Plateau Basalts (Lindsay et al., 2005).

In the Waterloo area, the Headley Limestone is on occasion observed lying directly upon the Antrim Plateau Basalts. In one particular locality Copper mineralisation has been observed within a 1 - 2m thick band of the Headley Limestone (Table 1 and Figure 1). This Cu mineralisation is hosted in a completely recrystallised carbonate as small 'asterisk'- shaped agglomerates of an as yet unidentified Cu carbonate mineral. This unit, which was only briefly investigated, appears to extend latterly for at least 40m; a second Cu show indicated on the Waterloo 1:250K Geological Map, ~5km to further south-west may indicate some degree of lateral continuity. The carbonate unit is underlain by a relatively fresh basaltic unit.

Interpretation:

The Daly Basin is a shallow intracratonic basin that formed at low latitudes (Torsvik et al., 2008b). Intracratonic basins that formed close the equator can contain Cu mineralisation as stratiform copper deposits, the most significant of which are the Kupferschiefer of north-central Europe, the Copper-belt of Central Africa, and the Manto Type Cu deposits of Chile in South America. These deposits are thought to form at the margin of intracratonic basins where warm, saline, oxidised basin-derived fluids interact with a suitable existing sediment horizon, these being typically pyrite- or evaporate-bearing shales or carbonates, causing Cu to be precipitated as Cu sulphides during redox reactions. Moreover, mineralisation is commonly associated with faults that act as fluid conduits.

The margins of the Daly Basin, therefore, appear to represent the ideal association of lithotypes, geological setting, and latitude to form a stratiform-type copper deposit. In addition, based on recent observation of basalt stratigraphy, there appear to be significant offset in the basalt stratigraphy, which may result from syn- and post-eruptive faulting in the area. The extent of this Cu-mineralisation, its relationship to the stratigraphy described, and elucidation of its occurrence with respect to the putative faulting remain to be confirmed through further fieldwork.

Recommendation:

Further field work to determine extent and geological relationships of this observed Cu-mineralisation is highly recommended integrated with mapping of the basalt stratigraphy.

This approach represents a cost-effective method of providing detailed reconnaissance data; this will be of value in establishing whether further geochemical or geophysical investigation is warranted. This mapping should include:-

1. Mapping the Headley Limestone outcrop in the Waterloo area in detail to ascertain the extent of mineralisation within the unit.
2. Investigate the faulting in the basalts that underlie the Headley limestone to assess whether or not these faults could be conduits for the hydrothermal fluids responsible for mineralisation in the limestone.

Part 4

Reconnaissance trip to the Wave Hill 'Vent Site' near Kalkarindji, Northern Territory

A brief, one day helicopter trip to the Wave Hill vent site was conducted in October 2010. The purpose of the site was to ascertain whether or not there was evidence for a volcanic vent in the Wave Hill area as postulated by Gole (2009). The putative vent is located at the western margin of a pronounced magnetic feature termed the 'Wave Hill Rill'. In all 4 sites of interest were identified using Google Earth imagery, and were visited during the trip (Fig. 3):

Site 1: The approximate position of the Wave Hill Vent site of Gole (2009)
Site 2: Unusual circular to oblate features 14km to the north of the Site 1
Site 3: Linear features observed during the flight 6km to the SW of Site 1
Site 4: A large elevated mesa 12km to the west of Site 1

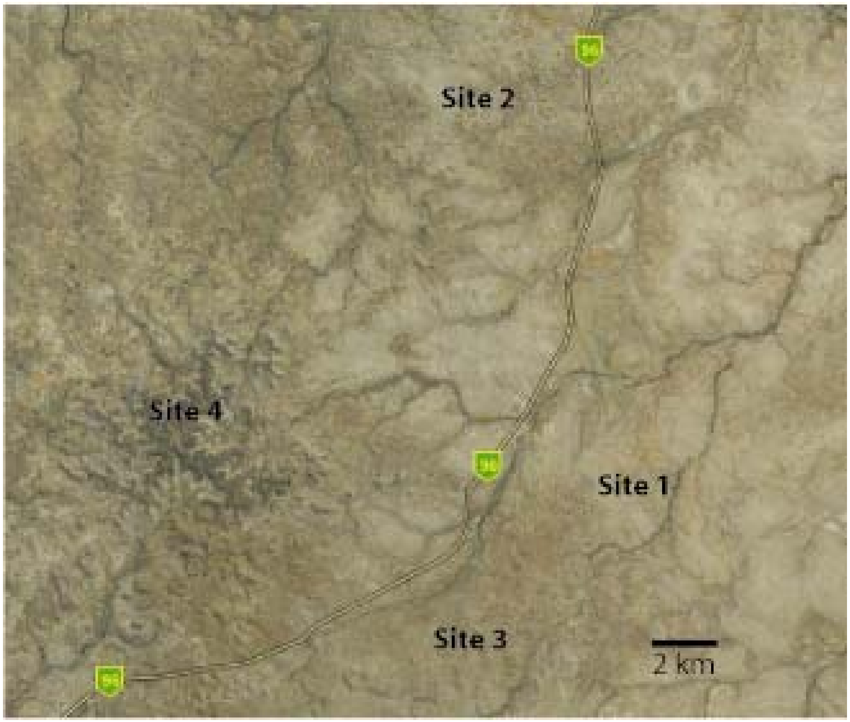

Figure 3: Location map of the 4 sites visited on the Wave Hill reconnaissance Trip.

Geology Observed

Site 1 A comprehensive investigation along stream sections traversed up to 0.5 - 1km from the helicopter landing site revealed no evidence of a proximal volcanic vent, or vent-type facies. A relatively typical basaltic lava flow was observed capping the broad, low hill that formed the landing site. This unit sits on top of a highly altered vesicular flow top observed in a gully 1 km to the west. In addition, a finely laminated chertified sedimentary layer (c. 50cm thick) was observed in the stream gully interposed between these two lava units. This sedimentary unit is interpreted as a depositional unit laid down during a prolonged eruptive hiatus.

Site 2 was investigated because of the presence of a significant number of elevated oblate to circular features between 50-100m in diameter in Google Earth. These features are intriguing 5 – 10 m high mesas consisting of laminated chert sucessions. In one location domed stromatolite-like structures were observed. This suggests that the chert may be replacing laminated stromatilitic limestone. The chert features are sitting above a relatively typical lava flow, and appear to be developed upon the upper lava flow at Site 1. There are numerous mesas of this type within a localised area of c. 25 km^3. They are here interpreted as the remnants of stromatolitic 'patch reefs' that developed in a shallow (brackish - saline?) water body that had become established in the area during a prolonged eruptive hiatus. These features are intriguing and worthy of further detailed investigation. In a broader context these, and the inter-trappean sediments observed lower in the basalt succession (Site 1), indicate that the arrival of lava units in the Wave Hill area was sporadic, and that the succession here represents interplay between volcanic and sedimentary environments during the evolution of the Kalkarindgi CFBP. Such intercalated environments are common in other CFBP successions (e.g. Columbia River and Deccan), though these are typically best developed around the periphery of the main lava fields, and distant from postulated vent sites (Jay and Widdowson, 2008; Jolley et al., 2008).

Site 3 was observed as the helicopter did a loop around Site 1 searching for any feature that might represent a volcanic vent. The feature eventually investigated was a series of northeast-southwest trending linear ridges close to the Buntine Highway. These features turned out to be steeply dipping metasediments forming a low (c. 2m high), continuous scarp.

Site 4 was a large elevated region (c. 10 km^2) to the west of Wave Hill. The helicopter landed on top of the highest mesa at the end of the trip; dense scrub vegetation and limited time constrained the detail of investigation. However, the mesa was dominated by a flat lying pahoehoe inflation unit with a rubbly flow top very similar to Unit A at Black Fellow Creek. This unit was overlain by a strongly weathered red brown volcanic unit. If this outcrop does represent an extension of the lava unit stratigraphy observed near Black Fellow Creek, then these lava units extend at least 200km distance.

Discussion

The primary objective of the trip to Wave Hill was to ascertain whether or not a volcanic vent could be discerned in the area. No evidence of a volcanic vent was apparent (e.g. vent agglomerate, or ash and scoriaceous deposits) after on ground investigation of the sites described above, and the aerial search revealed no obvious features that might represent a vent feature. Therefore, the nature of the Wave Hill Rill feature (Gole 2009) remains to be determined, and warrants further field-based and geophysical investigation.

Conclusions

See Executive Summary

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