Geochemistry and Geochronology Report, Volcanic Horizon Ooraminna-1 Core 16

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Location Ooraminna-1:

Ooraminnq-1 is a borehole located in central Australia just outside Alice Springs in the Northern Territory. The borehole was drilled into the Amadeus basin. The Amadeus basin is a Proterozoic basin located in central Australia situated between the North Australian Craton and the South Australian Craton lying directly above the Musgrave block (Figure 1). The Amadeus basin is a Mesoproterozoic – Late Devonian intraplate depression containing up to 14 km of sedimentary rocks (Camancho et al., 2015).

Hand Sample:

Half-core Medium fine grained with phenocryst of black and white to white-clear (plagioclase) minerals (0.5-2 mm) in a fine grained dark matrix. Some white veins roughly 1- 4 mm thick typically short in length (shorts is about 2 cm longest is about 4 cm before intersecting with the edge of the core). This volcanic horizon displays the presence of alteration with the presence of the post emplacement veins forming along cracks as well as a slight red coloration to the matrix and a green tint to some of the plagioclase phenocrysts.

Geochemistry Results:

Major Elements: The volcanic horizon falls into the basalt field in a total alkalis-silica (TAS) and just below the alkali – subalkalic line calculation of Irvine and Baragar (1971) (Figure 2). These volcanics display a moderately evolved signature with an MgO wt % of 7.96 and a SiO_2 wt % of 47.73 (Figure 3). The volcanic horizon has a low titanium concentration with a TiO_2 wt % of 1.81. The loss of ignition (LOI) for this volcanic horizon supports the altered nature of this sample with a value of 2.57 % indicating the sample is slightly altered. The LOI is a measure of the total volatile content within a rock; therefore the extent of weathering and alteration can be implied from these numbers, providing a first order quality estimate of the sample results. Anything greater than two is considered to have some form of alteration. Depending on the rock type, minerals of interest, and the hypothesis being asked this value could have different meaning when it comes to interpreting the results.

Trace Elements: The Core 16 volcanics display only a slight light rare-earth element (LREE) enrichment from the heavy rare-earth elements (HREE). The trend is nearly horizontal in the LREEs, with a slight Yb anomaly and no great Eu anomaly (Figure 4b). Although there is a slight enrichment in LREEs the deflection is almost not noticeable in a REE spider diagram normalized to CI Chondrites after Sun & McDonough (1989) indicating the petrogenesis of this volcanic did not preferentially take in any of the REEs over others to any extreme. Same can be observed in a trace element spider diagram, the overall trend of the trace element abundances displays an only slightly negative slope. The volcanics contain a negative Nb and positive Pb anomaly which indicates the influence of enriched material either through assimilation of continental material or through a direct enrichment of the source process. This volcanic horizon also displays a low Th and U abundance.

Geochronology Results:

In attempts to date the volcanic horizon of Core 16 from the Ooraminna-1 borehole plagioclase was separated from the samples for $^{40}Ar/^{39}Ar$ geochronology. As stated above the samples appeared in hand sample and the geochemistry to have suffered at least a slight degree of alteration. This was also apparent in the state of the plagioclase grains once the minerals had been separated. The plagioclase was typically a light green to white color. About 99-100 percent of the grains were cloudy with even the "cleanest" grains containing a degree of a white cloudy translucence. The most suitable plagioclase grains for $^{40}Ar/^{39}Ar$ analyses are transparent. Dark colored and white inclusions are avoided. The presence of sericite alteration in plagioclase is typical with only the slightest alteration. Sericite is a white mica that contains a high amount of K that can interfere with the measurement of the Ar produced solely within the plagioclase grains giving erroneous results. Due to the altered nature of this sample only 2 micrograms of plagioclase grains were recovered from about a 100 grains of crushed material for analyses. Even these 2 micrograms of plagioclase displayed a moderate degree of alteration apparent by the whity "cloudy" translucence of all the grains; this was considered to be sericite alteration of the plagioclase (plagioclase is not robust and is altered relatively easily). Although the alteration could not be avoided with this samples plagioclase grains the grains were still separated and analysed in hopes that even if an alteration age resulted something could still be learned about the history of this sample. Unfortunately the $^{40}Ar/^{39}Ar$ geochronological results were inconclusive due to excess Ar (Figure 5). This most commonly occurs from inside the system by the contamination by older grains such as soils during the eruption or ascent of the magma as one example; or by the introduction of Ar from outside the system.

What is expected in the diagrams presented in Figure 5 are a "plateau" formed by each of the step heating boxes graphed of no less than 70% to produce a reliably accurate and precise age. If the inconclusive results were the cause of sericite alteration primarily an abrupt change in the K/Ca ratio (increase) should be observed corresponding to a dip in the apparent age indicating sericite being heated or another type of inclusion. Many times even if there is sericite or another type of alteration affecting the formation of a plateau, an inverse isochron can be calculated using the measured $^{39}Ar/^{40}Ar$ and the $^{36}Ar/^{40}Ar$ (atmospheric Ar). If this was the case a model age could be calculated from the isochron for the material; however, excess Ar effects the whole system therefore the problem cannot be remedied by the separation and analysis of more material (thus increasing the measurable amount of Ar) or by a more careful separation of clean grains. Due to this an estimate on either the crystallization age or the alteration age cannot be made.

Discussion:

Kalkarindji Continental Flood Basalt Background: The Kalkarindji continental flood basalt province (CFBP) is composed of a number of lithostratigraphic units; the Antrim Plateau Volcanics, Milliwindi dolerite dyke, Nutwood Downs, Helen Springs, Peaker Piker, Colless Volcanics and the Table Hill Volcanics (Grey et al., 2005; Glass and Phillips, 2006; Evins et al., 2009; Pijajno and Hoatson, 2012). These scattered suites of the Kalkarindji province are exposed over about 425,000 km^2 (Veevers, 2001) of northern and central portions of Western Australia, much of the Northern Territory, western Queensland, and western South Australia. The original extent of the Kalkarindji CFBP has been estimated to be at least 2.1×10^6 km^2 making it one of the largest LIPs in the Phanerozoic (Evins et al., 2009).

The Antrim Plateau Volcanics is primarily composed of basaltic lava flows but also contains minor breccias and agglomerates, with the appearance of mainly discontinuous quartz sandstones, siltstones, chert, sedimentary breccia, and limestones intercalated with the lavas and breccias (Bultitude, 1976). The Antrim Plateau Volcanics compose the largest areal exposures of the Kalkarindji CFBP with a maximum thickness of about 1500 m west of Halls Creek, making up the thickest sections and the possible vent location for the Kalkarindji volcanics (Bultitude, 1976; Mory and Beere, 1988; Glass and Phillips, 2006; Evins et al., 2009). The Antrim Plateau Volcanics are exposed along the eastern extents of the Kimberly Region and forming the boundary between the eastern edges of the Victoria River Region and the western Wiso Basin. Exposures of the Peaker Piker Volcanics, Colless Volcanics, and Helen Springs Volcanics are found on the eastern and northern margins of the Georgia Basin. The Nutwood Downs Volcanics are exposed along the margins of the Daly River Basin. These areas of Kalkarindji are exposed as small outcrops and interbedded sediments separated from the Antrim Plateau Volcanics by younger basin fill sediments (Bultitude, 1976). The thicknesses of these outliers is significantly less than that found in the Antrim Plateau Volcanics; 122 m for the Nutwood Downs Volcanics, 37 m for the Helen Springs Volcanics and the Peaker Piker Volcanics, and 61 for the Colless Volcanics (Bultitude, 1976 *and references within*). Data from borehole samples have shown that the volcanics extend below the younger sediments of these basins giving a stratigraphic connection between many of the outcrops in the north (Bultitude, 1976) (Figure 1). The Table Hill Volcanics are a series of tholeiitic basalt outcrops exposed along the northern borders of the Officer Basin with subterranean units extending underneath much of the basin (Bultitude, 1976; Glass and Phillips, 2006; Evins et al., 2009).

Along with stratigraphic correlations geochemical studies conducted on these scattered suites of tholeiitic basalts have also suggested a similar parentage. The Kalkarindji CFBP is geochemically distinct from most flood-basalt sequences found elsewhere around the world, and rather resemble the Ferrar basalts. Kalkarindji rocks are characterized by relatively high SiO_2 and MgO, low TiO_2 and FeO_{total}, nearly consistent trace element ratios across the province, low high field strength element (HFSE) abundances relative to incompatible elements, and the most incompatible elements are extremely enriched (Bultitude, 1976; Glass, 2002; Glass and Phillips, 2006; Evins et al. 2009)(Figures 3 & 4). The Incompatible element signature of Kalkarindji suggests a crustal or enriched component into the magma source (Glass, 2002; Glass and Phillips, 2006; Evins et al., 2009). The enriched signature is homogenous across the province which differs from the typical eruptive unit restricted crustal contamination signatures found in most other continental flood basalts (Glass, 2002; Glass and Phillips, 2006) suggesting that this could be a lithospheric mantle enrichment effect rather than straight forward crustal contamination. Kalkarindji displays higher $^{87}Sr/^{86}Sr$ and lower $^{144}Nd/^{143}Nd$ ratios more analogous to Ferrar than to other large igneous provinces. Evins et al. (2009) found that the basalts became more fractionated in the main and late stages of eruptions showing the most primitive compositions at the beginning.

Initial age estimates for the Antrim Plateau Volcanics and thus the Kalkarindji CFBP were limited to inferences from stratigraphic relations. Early age estimates for this region was difficult due to the lack of diagnostic fossils within the interbedded sediments (Bultitude, 1976). Overlying and underlying stratigraphic relations indicate the Antrim Plateau Volcanics is older than the Middle Cambrian and younger than the Neoproterozoic (Bultitude, 1976). Recently high precision geochronology has been applied to the Kalkarindji CFBP to better constrain the timing and duration of this event; 513 ± 12 Ma using the U/Pb SHRIMP method on the Milliwindi dolerite dyke (Hanley and Wingate, 2000), a 508 ± 5 Ma U/Pb zircon analysis on the Boondawari dykes (MacDonald et al., 2005), recent higher precision $^{40}Ar/^{39}Ar$ analyses of 508 ± 2 Ma for the Helen Springs Volcanics, 505 ± 2 Ma for the Antrim Volcanics (Glass and Phillips, 2006), and 504.6 ± 2.5 Ma for the Table Hill Volcanics (Evins et al. 2009) (these ages have been recalculated with the three $^{40}Ar/^{39}Ar$ plagioclase ages ranging from 509.0 ± 2.6 Ma to 511.9 ± 1.9 Ma), and most recently ages of 510 ± 4 Ma ($^{40}Ar/^{39}Ar$), 511 ± 5 Ma and 510.67 ± 0.62 Ma (U/Pb TIMS) (Jourdan et al. 2014). All of these analyses have been able to constrain the age of Kalkarindji CFBP emplacement to around 510 Ma (Middle Cambrian).

Ooraminna-1 volcanic horizon compared to Kalkarindji CFB: The Amadeus basin currently lacks any evidence of the Kalkarindji CFBs. However the basin is located between the northern suite of the Antrim Plateau Volcanics and the southern suite of the Table Hill Volcanics. Therefore the discovery of a volcanic horizon within the Amadeus basin is of great interest for the continued study of the extent of the Kalkarindji CFBP. This could be due to the absence of Kalkarindji rocks being present at all in this area or the exposure of Proterozoic rocks within the basin today indicates that if any surface flows were present they would be long since eroded away. If the latter is the case that leaves the presence of Kalkarindji material to dykes and sills within the Amadeus basin. Unfortunately the geochronological analyses did not return any conclusive results to the age of this volcanic horizon. The geochemistry however can be used to an extent to determine if there is any correlation between the volcanic horizon found in the Ooraminna-1 borehole and the Kalkarindji CFBP. The major elements for the Core 16 volcanic horizon does overlap well in many instances with the Kalkarindji CFB; however, although the TiO_2 is less than two like the Kalkarindji rocks, the TiO_2 wt % for the Core-16 volcanic horizon is decidedly higher for that given Mg # than the Kalkarindji rocks (Figure 3). The biggest noticeable difference in the major elements between the Core-16 volcanics and the Kalkarindji rocks is the low SiO_2 wt % (Figure 3) and basaltic nature of the Core-16 volcanic horizon (Figure 2). All of the Kalkarindji CFBs fall into primarily the basaltic andesite field with some of the province falling into the basaltic trachy – andesite, trachy – andesite, trachyte, andesite, and dacite fields. This is a marked difference from the complete lack of basalts within the Kalkarindji CFBP. The trace elements signatures do overlap with the Kalkarindji rocks in most instances however, the most noticeable difference is the overall flatter trend in the data. This is attributed to the less enrichment in the LREE and the apparent lack of a Eu anomaly within this volcanic. In the case of the trace elements the most noticeable difference is the lower Th and U concentrations that the Kalkarindji CFBs. This could however be attributed to the different crustal type this volcanic horizon intruded compared to the much higher Th and U cratonal crustal types intruded by the Antrim Plateau Volcanic and the Table Hill Volcanic suites.

Conclusions:

The volcanic horizon found in Core-16 of the Ooraminna-1 borehole volcanics displays many similarities with the Kalkarindji CFBP. The major and trace elements are similar apparent form some noticeable differences in TiO_2 content for a given Mg#, the LREEs, and the Th and U content. Another glaring difference is the basaltic nature of the Core-16 volcanics which is in stark contrast to the complete lack of any rocks from the Kalkarindji CFBP falling within the basaltic field. Some of the geochemical differences in the Core-16 volcanic horizon could be attributed to the different crustal material this volcanic was emplaced into from the rest of the Kalkarindji province. Although the northern and southern suites of the Kalkarindji rocks are intruded into two different cratons similarities could be attributed to the intrusion through Archean basement for both suites that is most likely missing in the Amadeus basin region which is situated between cratons. It must be noted that even though the northern and southern suites intrude Archean basement the surface area of the Kalkarindji CFBP is very large indicating the intrusion through many different crustal types with almost no change in geochemistry found across the province, the Kalkarindji CFB displays homogeneous geochemical signatures. The most striking difference between the two volcanics is the basaltic nature of the Core-16 volcanics. Not only is the SiO_2 wt % lower than anything found in the Kalkarindji CFB the Core-16 volcanics do not fall within the trend observed in the Kalkarindji rocks. If they were related, and the slight other geochemistry differences could be attributed to slight differences in localized contamination, it would be expected that the alkali content (Na_2O + K_2O) would be much less at this low SiO_2. Without conclusive results from the geochronology therefore having to rely on the geochemistry alone it is difficult to determine if this volcanic horizon is a part of the Kalkarindji CFBP. Alteration could be the cause of some of the differences in trace element geochemistry observed between the Kalkarindji CFBs and the Core-16 volcanic horizon; however, the striking difference between these two volcanics in SiO_2 wt % and falling off the "trend" or the Kalkarindji CFBs observed in the TAS diagram leads toward the conclusion that they are not related.

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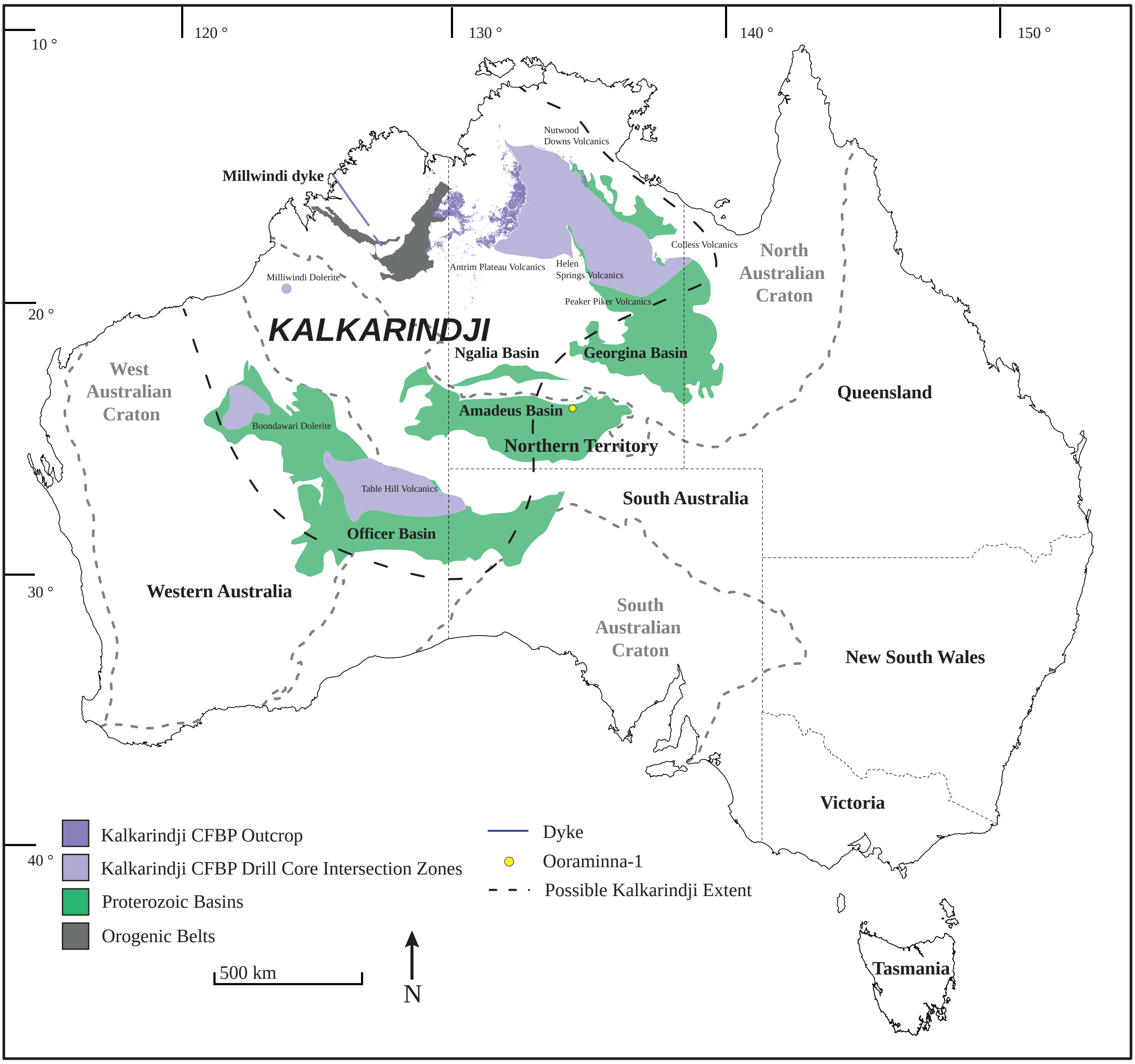

Figure 1: Sketch map of the Kalkarindji continental flood basalt province's distribution and constituent suites. Prevalent Proterozoic basins residing locally to Kalkarindji are also displayed. Modified and created from Jourdan et al. (2014), and Glass and Phillips (2006) Australian crustal elements from Shaw et al. (1995).

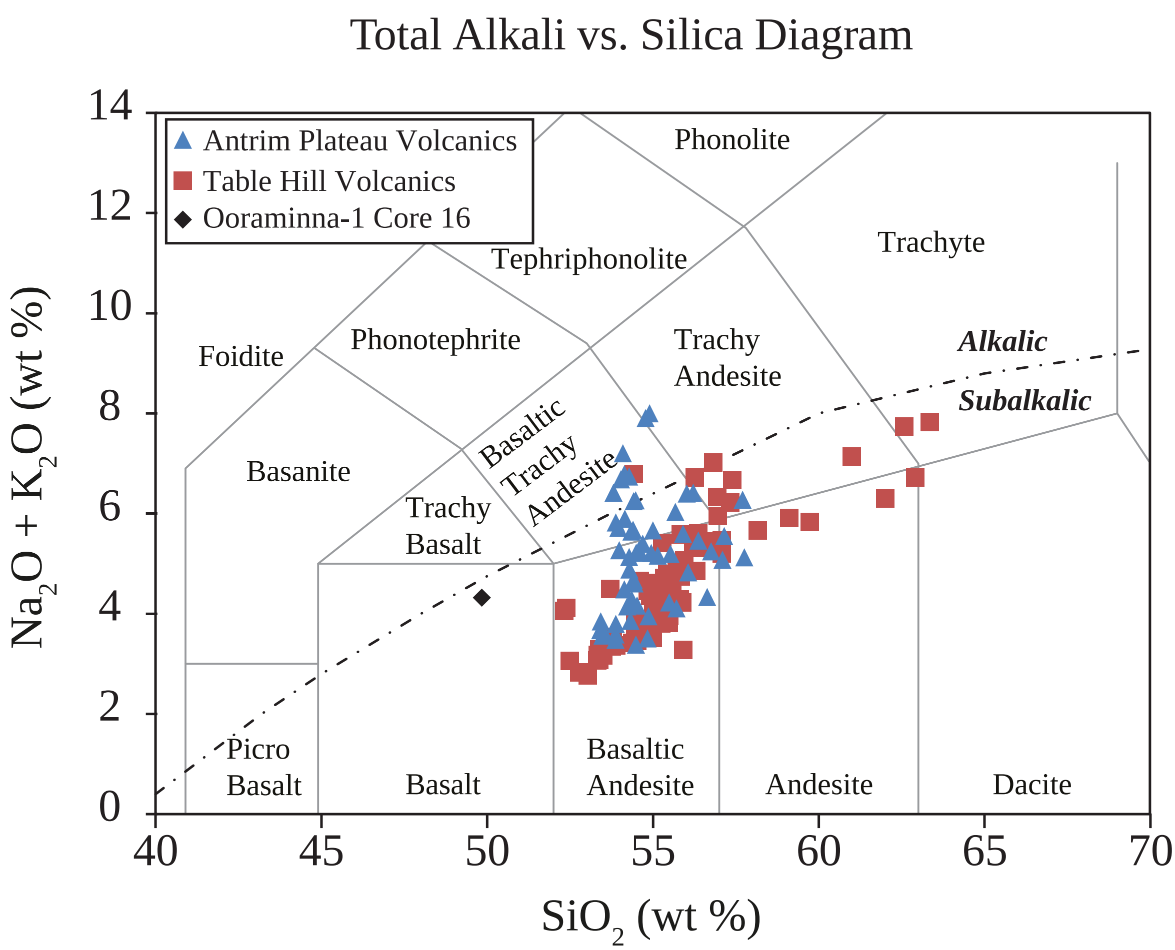

Figure 2: Total alkalis-silica (TAS) Diagram, [Le Bas et al. (1986)]. Alkalic – subalkalic line calculated from Irvine and Baragar (1971).

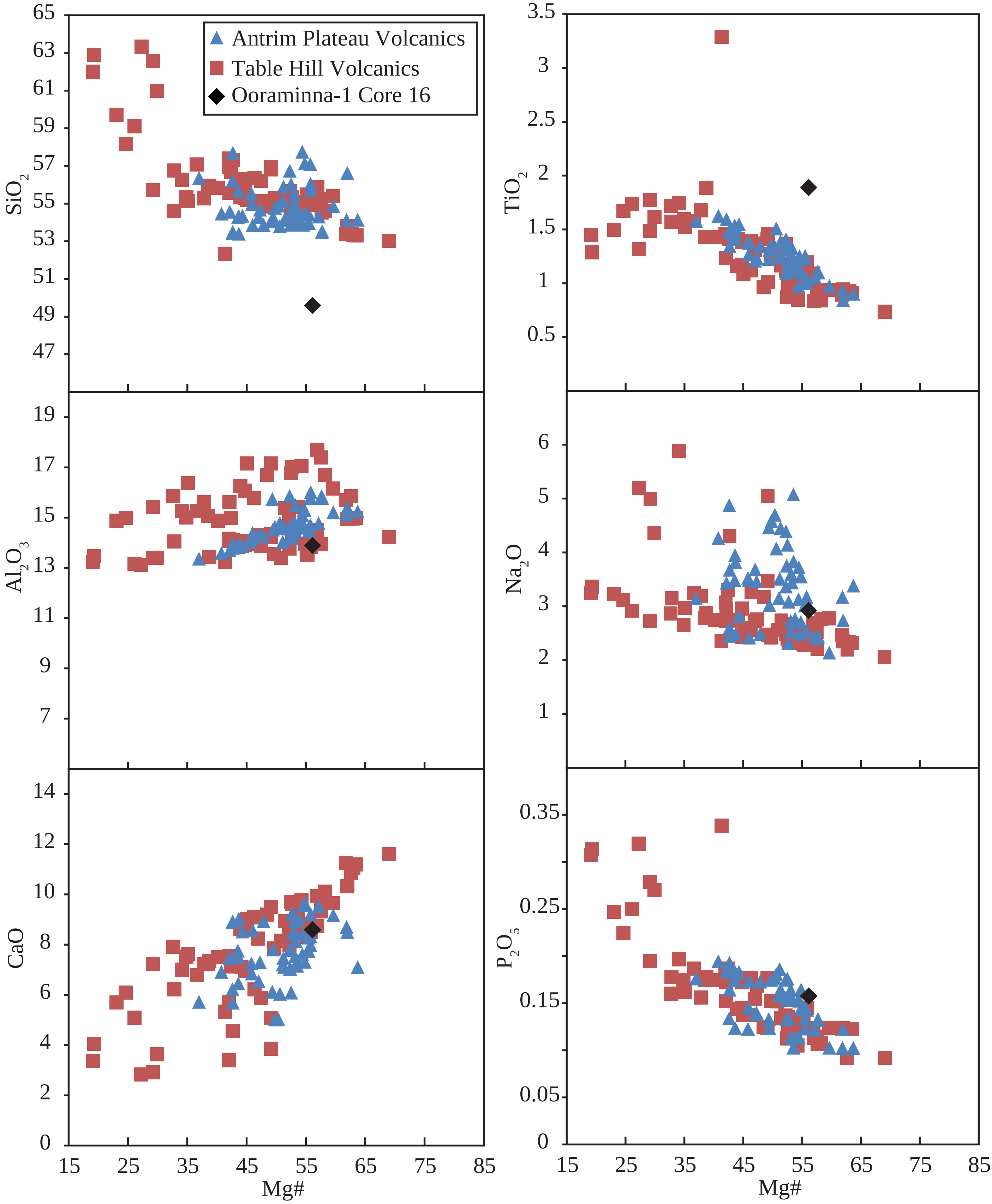

Figure 3: Major element (wt %) vs. Mg – number [100 x atomic ratio of Mg/ (Mg + Fe^{2+}) with Fe_2O_3/FeO normalized to 0.15] diagrams.

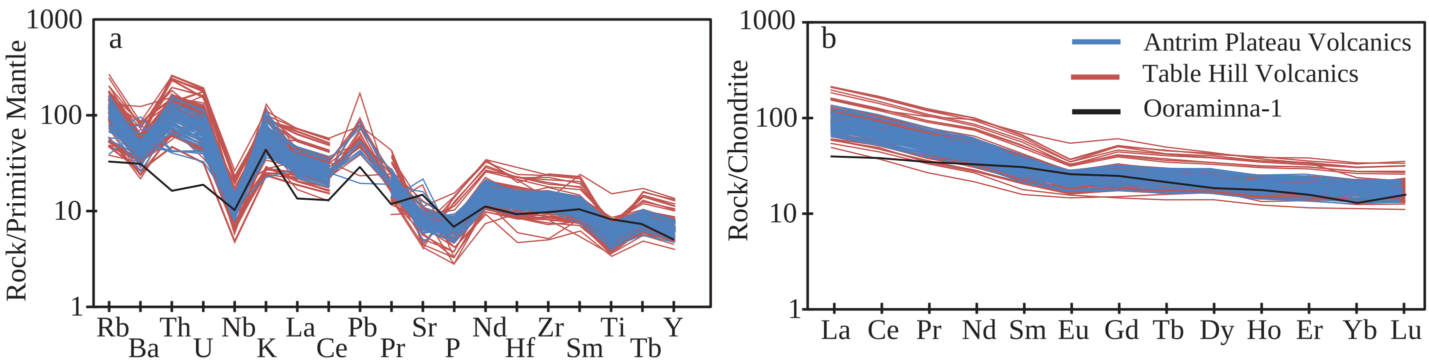

Figure 4: (a) Primitive mantle normalized incompatible trace elements patterns for the Kalkarindji CFBP. (b) Chondrite – normalized REE patterns for the Kalkaringji CFBP. Normalization parameters from Sun and McDonough, 1989.

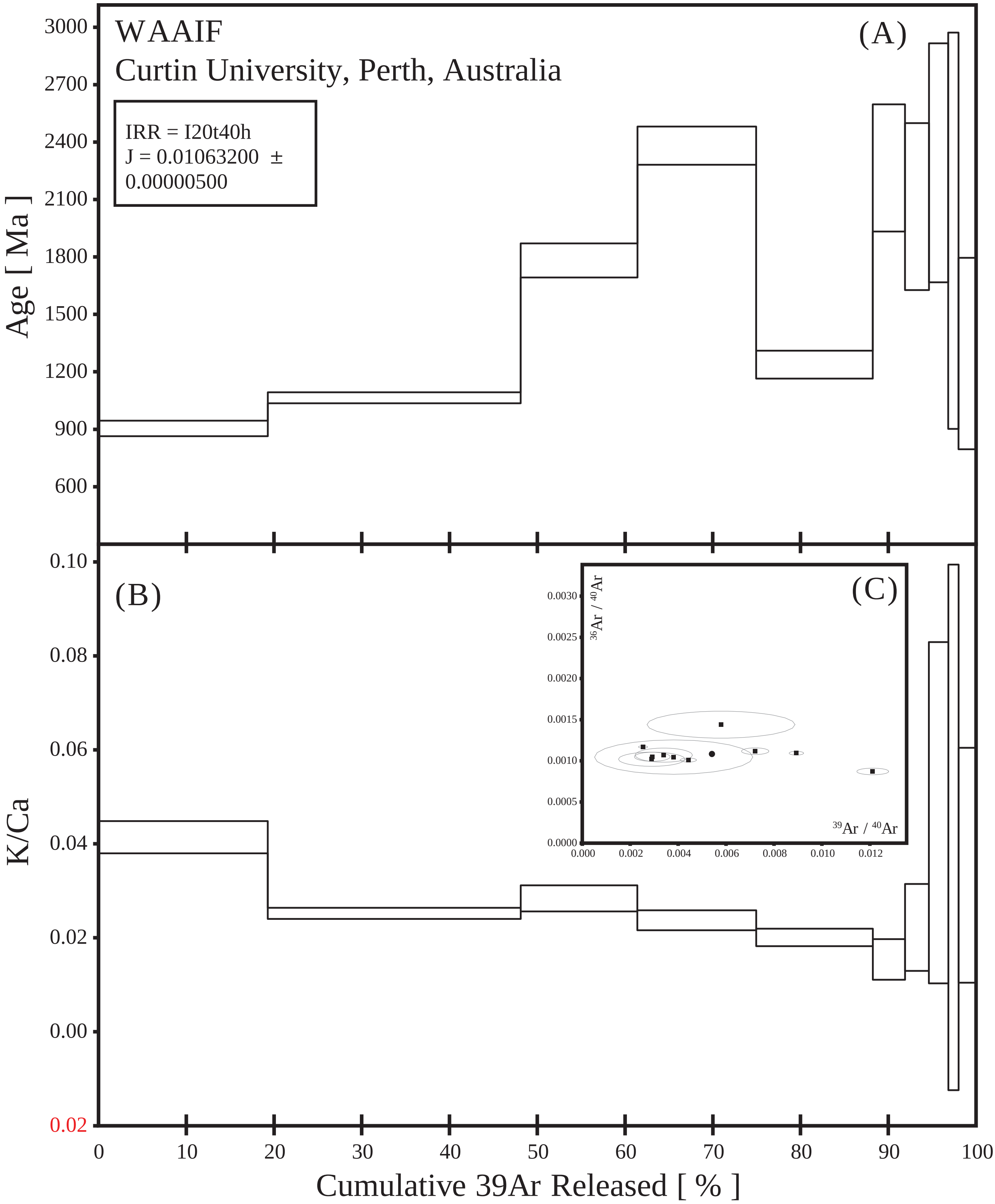

Figure 5: $^{40}Ar/^{39}Ar$ apparent age (A) and K/Ca ratio (B) spectra for 2 micrograms of separated plagioclase from the Ooraminna-1 Core 16 versus the cumulative percentage of ^{39}Ar released. Errors on plateaus are 2σ and do not include systematic errors (i.e. uncertainties on the age of the monitor and on the decay constant). (C) $^{36}Ar/^{40}Ar$ vs $^{38}Ar/^{40}Ar$ plot.