The Discovery and Geology of the Timber Creek Kimberlites, Northern Territory, Australia

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ABSTRACT

Five kimberlites were discovered between 1991 and 1993 by Stockdale Prospecting Limited (SPL), a wholly owned subsidiary of De Beers, approximately 350km due south of Darwin, in Australia's Northern Territory. The kimberlites intrude early to mid Proterozoic limestones and dolomites of the Victoria River Basin (VRB) and are the only known kimberlites within the basin. The nearest known diamondiferous intrusive is the Argyle Lamproite, some 250km to the southwest. The kimberlites were discovered using conventional heavy mineral stream and loam sample techniques. Brittle chromian spinel was the principle indicator mineral observed, although mantle zircon macrocrysts were recovered from Timber Creek-01 (TC-01). Chromian spinels generally have both high Cr_2O_3 (>50%) and high MgO (>8%) contents. The zircons contain similar mineral chemistries and cathodoluminescence properties to zircons recovered from southern African, Yakutian and Australian kimberlites.

TC-01 was the first intrusive discovered and occurs as a small pipe-like outcrop of highly silicified and brecciated hypabyssal facies kimberlite approximately 50m in diameter. The remaining four kimberlites (TC-02 to 05) appear to be dykes or dyke swarms and are located within a two kilometre radius of TC-01. Mineralogically, they are classified as macrocrystic probable Group 1 phlogopite - monticellite kimberlites.

Diamonds have been recovered from TC-01, 02 and 04. Diamond recovery has not been attempted for the other two kimberlites, although chromian spinel chemistry would suggest they have either very low diamond grades or are barren. Fine diamond analysis of drill spoils from TC-01 suggest that it may have a grade in excess of 100 CPHT. Ion microprobe (SHRIMP) dating of Timber Creek zircons yields a mean $^{206}Pb/^{238}U$ age of 1462 ± 53Ma and Fission Track analyses of Timber Creek zircons gives a date of 1038 ± 66Ma.

Keywords: Australia, kimberlite, diamond, chromian spinel, geochemistry, petrography, zircon

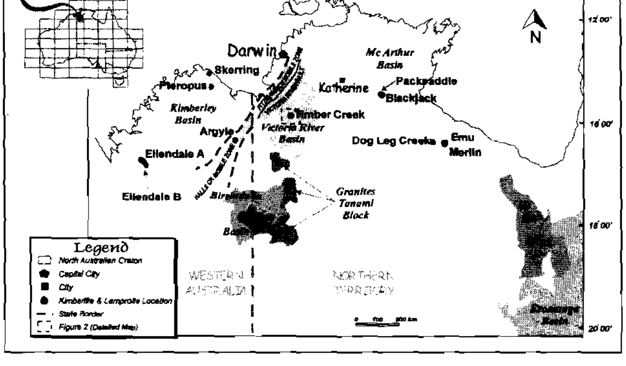

Figure 1. Location Map, Timber Creek Kimberlites.

1. INTRODUCTION

The North Australian Craton (NAC) and the Kimberley area of Western Australia have long been the target of intense diamond exploration. Kimberlitic rocks were identified in the Kimberley region as early as 1976 with the discovery of the Pteropus and Skerring kimberlite pipes, followed by the Ellendale lamproite fields and finally the Argyle lamproite in 1979 (Jaques *et al.*, 1986). Diamonds have been discovered in prospecting samples across most of the NAC and appear to be concentrated in the Coanjula area of the Northern Territory. In this latter area the diamonds are believed to be largely derived from metamorphic Proterozoic greywackes (Lee *et al.*, 1994), rather than primary kimberlitic source rocks. The Emu pipes were discovered one hundred and thirty kilometres to the north of Coanjula in 1984 (Smith *et al.*, 1990), near what is now known as the Merlin Field (Fig. 1).

Although little was known about the basement age of the NAC at the time, the wide distribution of diamonds and the Emu discovery encouraged Stockdale Prospecting Limited (SPL), a subsidiary of De Beers, to explore the NAC within the Northern Territory. The western McArthur Basin and the Victoria River Basin were initial targets as both have well developed drainage amenable to heavy mineral stream sampling.

Between 1983 and 1985, single garnets were recovered from a number of localities in the Roper River region of the McArthur Basin. Stream infill and loam sampling led to the discovery of the Packsaddle kimberlite. Drilling outlined a series of en echelon dykes trending approximately 330° for 2km along the base of a small scree slope. Subsequent sampling of the dykes showed they were garnet-rich, hypabyssal facies Group 1 kimberlites. Further reconnaissance led to the discovery of the chromian spinel-rich Blackjack kimberlite dyke, some 10km to the southeast. The dyke has a similar strike to Packsaddle and extends for a little over 1km. Both kimberlites are diamondiferous.

Follow-up of two brittle chromian spinels recovered in the Timber Creek area of the Victoria River Basin (Fig. 1) led to the discovery of five kimberlites by SPL between 1991 and 1993. These kimberlites were the first to be found within the Proterozoic Victoria River Basin (VRB). The kimberlites are located within a 2km radius of TC-01, the first and largest discovered. Three of the kimberlites (TC-01, TC-02 and TC-04) are diamondiferous.

The Timber Creek kimberlites can be distinguished from each other on the basis of their mineral chemistry, geochemistry and alteration characteristics. This paper describes the exploration techniques employed to locate the kimberlites, and the petrology and geochemistry of these rocks.

2. GEOLOGICAL SETTING

The North Australian Craton is believed to have been consolidated by 1830Ma (Myer *et al.*, 1996) as a result of the accretion of older crustal fragments. At that time, the main components of the craton were the Kimberley Craton, the Pine Creek / Rur

Jungle Orogen, and the Lucas Craton, largely comprising the Granites - Tanami region (Fig. 1).

Recent teleseismic investigations (SKIPPY Project – Australian National University) indicate that the NAC east of the Halls Creek Mobile Zone is a region with high shear wave speed suggesting the presence of thick lithosphere. At a depth of 200 kilometres, the high wave speeds continue as far east as the Eromanga Basin and the Mt Isa Inlier. In contrast, the Kimberley Block has lower wave speeds (van der Hilst and Kennett, 1997).

The Timber Creek Kimberlites are situated wholly within the Proterozoic Victoria River Basin (VRB), which is a major component of the NAC (Fig. 1,2). The VRB consists of both marine and continental sediments, with a maximum thickness of about 3500m (Palfreyman, 1984). Marine sediments originate from either shallow water or littoral environments, as evidenced by ripple marks, mud cracks, algal layering and halite pseudomorphs. No Archaean material is exposed within the VRB.

Initial work (Sweet, 1977) suggested that sedimentary deposition of the VRB took place around 1200Ma, although Timber Creek emplacement dates and recent work by the Northern Territory Geological Survey indicate that deposition may have been contemporaneous with that in the Birrindudu Basin to the south (1560Ma, Myer *et al.,* 1996). Both basins appear to have similar coherent geophysical domains (Shaw *et al.,* 1996) providing further evidence for synsedimentary deposition. Pontifex and Sweet (1972) believe that the VRB has undergone at least three periods of gentle folding and warping. The nearest major fault to the kimberlites is the Victoria River Fault, 90 km to the northwest, which divides the Fitzmaurice Mobile Zone from the VRB.

The kimberlites intrude the Timber Creek Formation, which is the lower most unit of the Adelaidean Bullita Group, one of the stratigraphic units comprising the VRB (Fig 2). The Timber Creek Formation consists of interbedded dolomites, shales and siltstones. No accurate age determination is available for the Bullita Group, and ages for overlying units elsewhere within the VRB are poorly constrained. There is little evidence of host rock deformation around the kimberlites, although the area is bisected by a number of goethite and barite-rich fault breccias, which strike at approximately 300°.

3. EXPLORATION HISTORY

The VRB was first targeted for exploration by SPL in 1987. The relatively stable Proterozoic Basin was considered a potential host for kimberlites and was generally well drained, making it suitable for heavy mineral stream sampling. Initial reconnaissance exploration involved the collection of stream samples at an approximate density of 1 sample per 10 square kilometres. Samples generally consisted of 100 litres of gravel, screened to -2.0mm in the field. Two chromian spinel grains were recovered from a drainage 10 km south of the Timber Creek township (and ultimately 1.5 km downstream from TC-01). The two spinels were considered anomalous as they were unexplained by either mapped or observed geology.

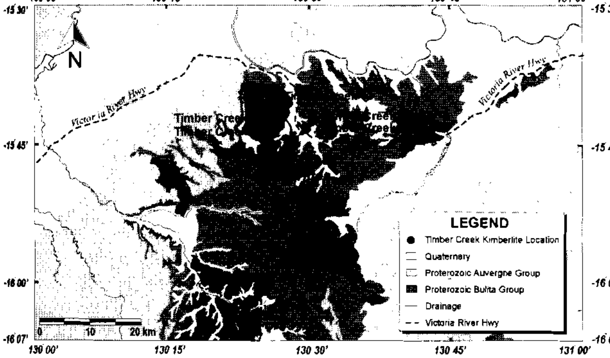

Figure 2. Geology, Timber Creek Kimberlites

A subsequent attempt to repeat the results recovered two additional chromian spinels. Further infill stream sediment sampling upstream from the trigger sample provided the first real clue that rocks of interest were present, and two small valleys were selected for further follow up. Both valleys were covered by a 50m interval loam sample grid. Samples consisted of approximately 40 litres of both deflation and regolith material scraped from an area of approximately 3 square metres. One sample at the base of a scree slope contained 17 diamonds (between 0.3mm and 1mm) and numerous chromian spinels. The Timber Creek-01 kimberlite was identified in outcrop approximately 30m up slope. This occurrence is approximately 50 metres in diameter and is believed to be either a small pipe or a blow on a dyke.

Loam sampling was then expanded to broaden the search area. Samples were collected at varying intervals (although never more than 200m spacing). A number of chromian spinel anomalies were identified, some of which were associated with an allied diamond anomaly. It should be noted that no diamonds were discovered in stream samples during prospecting. Scattered chromian spinels were recovered within a 2km radius of the known kimberlites, but further soil sampling suggested that the majority of these grains were transported from the kimberlites by extensive wet season floods. TC-02 and TC-03 were discovered by ground inspection upstream of two of the spinel anomalies, whereas TC-04 and TC-05 were discovered by drilling spinel anomalies. A number of goethite and barite-rich fault breccias were identified in the immediate area, although the only kimberlite to be associated with these features was TC-04. The kimberlite dykes and fault breccias strike at between 280° and 310° and are less than 1 metre wide. Kimberlites TC-01 to 04 are exposed at the surface.

All heavy mineral samples were screened to -2.0mm, although usually only the -1.0+0.3mm material was examined. The spinels recovered in heavy mineral samples are very brittle. Recent tests suggest that spinels do not survive transportation within this stream environment beyond about 2km from their source.

Following the discovery of TC-01, satellite imagery, aerial photographic surveys, aerial and ground magnetics, and input EM were all employed as exploration techniques in an attempt to identify new kimberlites, as well as to define the size of those kimberlites already located. None of the bodies can be seen using these remote sensing techniques due to the small size of the kimberlites and the high degree of alteration.

4. ANALYTICAL TECHNIQUES

Geochronology

Ten zircons were dated using the ion microprobe (SHRIMP) at the Australian National University. Standard analytical techniques where used, and these are fully described by Compston *et al.* (1992). The analyses consist of 6 scans through a mass range, which included the analyses of a standard SL13 zircon. Thirteen analyses were carried out, with each of the zircons being analysed at least once. Due to the low abundance of U in the measured grains, the measured $^{207}Pb/^{206}Pb$ ratios and calculated $^{207}Pb/^{206}Pb$ ages are imprecise, so the estimated ages of the zircons were determined from the weighted mean $^{206}Pb/^{238}U$ age. The zircon fission track analyses of seventeen grains was carried out by Geotrack using the external detector method. Analytical details are summarised by Gleadow *et al.* (1976) and Hurford and Green (1982).

Mineral Chemistry

Spinels from heavy mineral concentrates were analysed for major elements by electron microprobe using standard procedures as outlined by Pouchou and Pichoir (1984) utilising the Cameca SX-50 microprobes at Melbourne University and Anglo American Research Laboratories, Johannesburg.

Trace elements in zircons were analysed using the laser-ablation ICPMS microprobe at Macquarie University. Detailed descriptions of instrumentation, analytical and calibration procedures are given by Norman *et al.* (1996). The UV laser ablation microprobe is coupled to a Perkin-Elmer Elan 5100 ICPMS. Detection limits are typically less than 0.3 ppm for the REE, Y, P, Th and U. All analyses have been done with a pulse rate of 4 Hz and a beam energy of 1 mJ per pulse, producing a spatial resolution of approximately 50 microns in the zircons. Quantitative results for 28 elements were obtained through calibration of relative element sensitivities using the NIST-610 glass as external standard, and normalisation of each analysis to the electron-probe data for Hf as an internal standard. The precision and accuracy of analysis are ±2 - 5%, and up to ±10% for Fe and for other elements with concentrations less than 1 ppm.

Geochemistry

Rock samples from each of the five kimberlites were sent to Anglo American Research laboratory for 36 element XRF whole rock analysis. The samples were washed, dried and subsequently crushed to fragments less than 1cm in a roll jaw crusher and then pulverised in a carbon steel mill. All equipment was thoroughly cleaned between samples. XRF analyses were performed on a Phillips PW 1401 X-Ray Fluorescence Spectrometer. Major elements were determined on flux-fusion discs by mixing 0.35g of milled sample with 0.9g of flux, and trace elements were determined on pressed powder-pellets which were made by mixing 8-10g of milled sample with a binding agent, after the method of Norrish and Hutton (1969). The lower limit of detection for each of the major elements is as follows: SiO_2 and TiO_2 (0.004%), Al_2O_3 (0.005%), Fe_2O_3, P_2O_5 and MnO (0.001%), MgO (0.011%), CaO and K_2O (0.0003%), and Na_2O (0.018%). Detection limits for trace elements are: Ba (1.0ppm), Cr (0.6ppm), V (0.5ppm), and Rb (0.4ppm). All remaining trace elements have lower limits of detection of less than 0.3ppm. Where available, both surface and drill samples were tested.

5. GEOCHRONOLOGY

Stratigraphic relationships show that the age of the host rocks for the kimberlites, the Adelaidean Timber Creek Formation, is constrained by dates of overlying units, which range from 1066-1094Ma (K-Ar on basal sandstone glauconite of Wondoan Hill Formation) to 1124-1190Ma (Rb-Sr on same glauconite), Sweet (1977). However, recent investigations by the Northern Territory Geological Survey (S.Abbott, D.Young, pers.com.) recognise correlation's between sediments of the Victoria River Basin and the McArthur Basin, and suggest that the Timber Creek Formation may be older than 1490Ma.

The highly weathered nature of the kimberlites has made a direct age determination difficult. Consequently, a bulk sample comprising 84 tons of colluvium, screened to -4.75mm, was collected below the Timber Creek-01 occurrence in an attempt to extract diamonds with inclusions for dating. Although 1913 diamonds (19.83 carats) were found, unfortunately no useful inclusions were identified. However the sample did contain a number of mantle zircons which are believed to be kimberlite megacrysts. The grains are large anhedral crystals devoid of any significant zoning, and have extremely low U and Th contents (Table 1). Grains exhibiting various colours were selected for SHRIMP dating. Thirteen analyses were carried out, yielding ages of between 1384Ma and 1557Ma, with a mean $^{206}Pb/^{238}U$ age of 1462 ± 53Ma (Armstrong, 1995). A summary of ion microprobe U-Pb results is listed in Table 1. An additional fifty zircons, again of variable colour, were submitted to Geotrack for fission track analysis. Track counts for seventeen grains gave a pooled fission track date of 1038 ± 66Ma (Green, 1996), which is the age at which the grains cooled through the 300 to 250°C temperature range.

The zircon SHRIMP date puts emplacement at or near the more recent estimated depositional age of the Timber Creek Formation. The fission track age is more in line with previously accepted ages for the local geology and the emplacement age of the Argyle lamproite at 1178 ± 47 Ma (Rb-Sr total rock, Pidgeon *et al.,* 1989). Unfortunately the variation in ages is yet to be

Table 1. Summary of ion microprobe U-Pb results of zircons from Timber Creek 01.

Grain spot	U (ppm)	Th (ppm)	Th/U	Pb (ppm)	$^{204}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	± (1 sigma)	AGE (Ma)	± (1 sigma)
1.1	7	4	0.54	2	0.003131	0.2576	0.0175	1478	90
1.2	5	2	0.42	1	0.002092	0.2402	0.0156	1388	81
2.1	8	5	0.62	2	0.003932	0.2554	0.0137	1466	71
3.1	6	2	0.40	2	0.001256	0.2566	0.0130	1473	67
4.1	8	3	0.44	2	0.003994	0.2594	0.0172	1487	89
5.1	5	2	0.39	1	0.005277	0.2394	0.0180	1384	94
5.2	10	5	0.48	3	0.002673	0.2503	0.0141	1440	73
6.1	8	4	0.46	2	0.001499	0.2604	0.0134	1492	69
7.1	7	4	0.58	2	0.002976	0.2477	0.0163	1427	85
8.1	5	2	0.35	2	0.000155	0.2732	0.0192	1557	98
9.1	6	3	0.47	2	0.003116	0.2477	0.0136	1427	71
10.1	5	2	0.39	1	0.006650	0.2650	0.0219	1515	112
10.2	5	2	0.37	1	0.006356	0.2675	0.0177	1528	91

resolved, but kimberlitic emplacement is at least constrained between approximately 1000Ma and 1500Ma. Further work will be required to determine the true age of both the kimberlite intrusion and the host rock geology.

6. PETROGRAPHY

All five Timber Creek kimberlites have been extensively altered. Therefore, emphasis is placed on careful examination of textures, rather than primary mineralogy, in the identification of constituents within the Timber Creek petrological samples. Some 30 thin sections, obtained from a variety of surface and drill hole samples of the five known Timber Creek kimberlites, were examined.

Macroscopically the Timber Creek samples are characterised by a distinctive inequigranular texture due to variable modal proportions of country rock xenoliths (mainly quartz arenites, quartzites and mudstone/shale, as well as less common limestone/dolomite), and pseudomorphs after olivine (macrocrysts and phenocrysts). All samples have been affected by a range of additional secondary alteration processes, including silicification, ferruginisation, carbonatisation and clay formation, which have destroyed much of the primary mineralogy, including any preceding serpentinisation and steatitisation. Carbonatisation is limited to the Timber Creek -01, -02 and -05 occurrences, whereas silicification and ferruginisation are common to all the intrusions. No obvious macroscopic mantle- or lower crustal-derived xenoliths are visible in any of the samples.

Thin section examination confirms the presence of predominantly silicified and ferruginised pseudomorphs after olivine macrocrysts and phenocrysts, set in a finer-grained texturally and mineralogically modified matrix. In general the macrocrysts are distinguished by being larger and more rounded than the phenocrysts, which tend to be more euhedral (Clement *et al.*, 1984). The macrocrysts are up to 6mm in diameter and comprise up to 20 modal percent. The primary modal proportion has however been obscured by the alteration. The euhedral phenocrysts may reach up to 2.5mm (0.7mm on average).

Totally silicified olivine macrocrysts and phenocrysts can be distinguished from the silicified groundmass by the coarse, irregular and recrystallised appearance of the quartz, and the paucity of fine-grained groundmass spinel and other inclusions in the former (eg. in samples from Timber Creek-01). Quartz grains within the quartz arenite and quartzite xenoliths are well rounded and often exhibit characteristic authigenic overgrowths, allowing for easy recognition of the country rock xenoliths (e.g. Timber Creek-03).

Identification of the primary groundmass assemblage is mainly based on samples from Timber Creek-02, which exhibit the best preservation, and most likely originally consisted of accessory apatite, groundmass spinel, and phlogopite. Monticellite is tentatively identified as an additional groundmass mineral due to the presence of rare, indistinct granular relicts generally less than 0.05mm in size, within the groundmass. Perovskite has not been identified in any of the samples, although this may be an artifact of the alteration. Apatite is best preserved in Timber Creek-05 where it occurs as small discrete prismatic laths and hexagonal basal sections ranging from less than 0.01mm to 0.05mm in length. Euhedral, equant groundmass spinels are somewhat more ubiquitous and range up to 0.06mm in size. Groundmass phlogopite is best preserved and most common in samples from Timber Creek-02, where it occurs as prismatic, bleached and partly altered laths ranging up to 0.2mm in length. The substantial modal abundance suggests that phlogopite was a major groundmass component. Samples from the remaining Timber Creek kimberlites also contain some of these minerals, eg. phlogopite and particularly spinel, but are generally considerably more altered. Secondary groundmass minerals typically include quartz, haematite, goethite, calcite, dolomite, mica and clay minerals.

The presence of altered olivine macrocrysts and phenocrysts, the brecciated appearance of the samples, and the groundmass mineral assemblage, in combination with other features such as the presence of diamonds, indicator mineral chemistry and whole rock geochemistry, have convincingly shown that the Timber Creek occurrences can be classified as hypabyssal facies macrocrystic kimberlites. Mineralogically, these intrusions are best classified as phlogopite-monticellite kimberlites or phlogopite kimberlites.

7. MINERAL CHEMISTRY

Heavy Mineral Concentrates

The heavy mineral concentrates of all the Timber Creek Kimberlites are dominated by chromian spinel. No other typical kimberlitic indicators were discovered in exploration samples, although mantle-type zircon (U=5-10ppm, Th=2-5ppm) was identified on the surface near TC-01 and almost certainly is derived from the kimberlite. Diamonds were recovered from HF-digested rock samples of TC-01, 02 and 04 and from surface samples close to TC-01 and TC-04.

Spinels

The major element chemistry of spinels from the Timber Creek kimberlites varies considerably. Spinel mineral chemistry plots for TC-01 and TC-03 are shown in Fig. 3(a-d), and for TC-04 surface and drill samples in Fig. 4(a-d). Spinel composition plots for TC-05 and TC-02 are not shown, but closely resemble TC-01 and TC-03 respectively. The spinel populations are either tightly constrained, as is the case for TC-01 and TC-04 (drill sample), or show a more typical mantle spinel spread, as is the case for TC-03 and TC-04 (surface sample). Most spinels from the tightly constrained populations have >50 wt% Cr_2O_3 and generally < 1 wt% TiO_2. The spinels from those kimberlites displaying less tightly constrained populations contain spinels with between 25 and 65 wt% Cr_2O_3 and highly variable TiO_2 (between 0 and 8 wt%). In both cases, the spinels generally have >10 wt% MgO. All of the kimberlites have spinels within the diamond intergrowth / inclusion fields (Fipke *et al.*, 1995), although only the TC-04 surface sample, and the TC-01 sample to a lesser degree, can be considered high diamond potential bodies based on spinel mineral chemistry. Note that the TC-04 kimberlite actually appears to be a dyke swarm. The kimberlite on surface is mineralogically different from the kimberlite intersected by the drill at depth and this probably accounts for the difference in the spinel populations between the TC-04 drill and surface samples (Fig 4).

ZnO and Al_2O_3 contents of spinels are highly variable among the kimberlites. In general, Al_2O_3 is between 8 and 20 wt%, although the lower interest kimberlites (TC-02 and TC-03) have a high percentage of grains with Al_2O_3 values between 20 and 40wt%. ZnO is generally less than 1 wt%, although TC-01 has a low Al_2O_3 population of spinels (< 8wt%) with ZnO values as high as 5wt%. High ZnO within kimberlitic chromian spinels has been attributed to the replacement of MgO with ZnO and/or MnO in the Nabberu area of Western Australia (Shee *et al.*, 1998). At Timber Creek the high ZnO content may therefore represent late stage metamorphism or deep weathering and is perhaps a function of the age of the kimberlites.

The spinels are generally anhedral and many are cracked and have a sugary external surface. Corona development is seen on spinels from all five kimberlites. Six percent of TC-03 spinels, 17% of TC-04 and 3% of TC-05 spinels have coronas. The contact between the corona and the spinel core is generally irregular and embayed. The spinel coronas usually exhibit some depletion of MgO and moderate depletion of Cr_2O_3, along with increases in both TiO_2 and ZnO as compared to the grain core. This TiO_2 enrichment probably results from 'xenocrystic' spinel that is overgrown and/or reacting with high TiO_2 'phenocrystic' spinel crystallising from the kimberlitic magma (Grutter and Apter, 1998). The brittle and fragile nature of these 'overgrowths' accounts for the observation that they are only found close to the actual kimberlite outcrop.

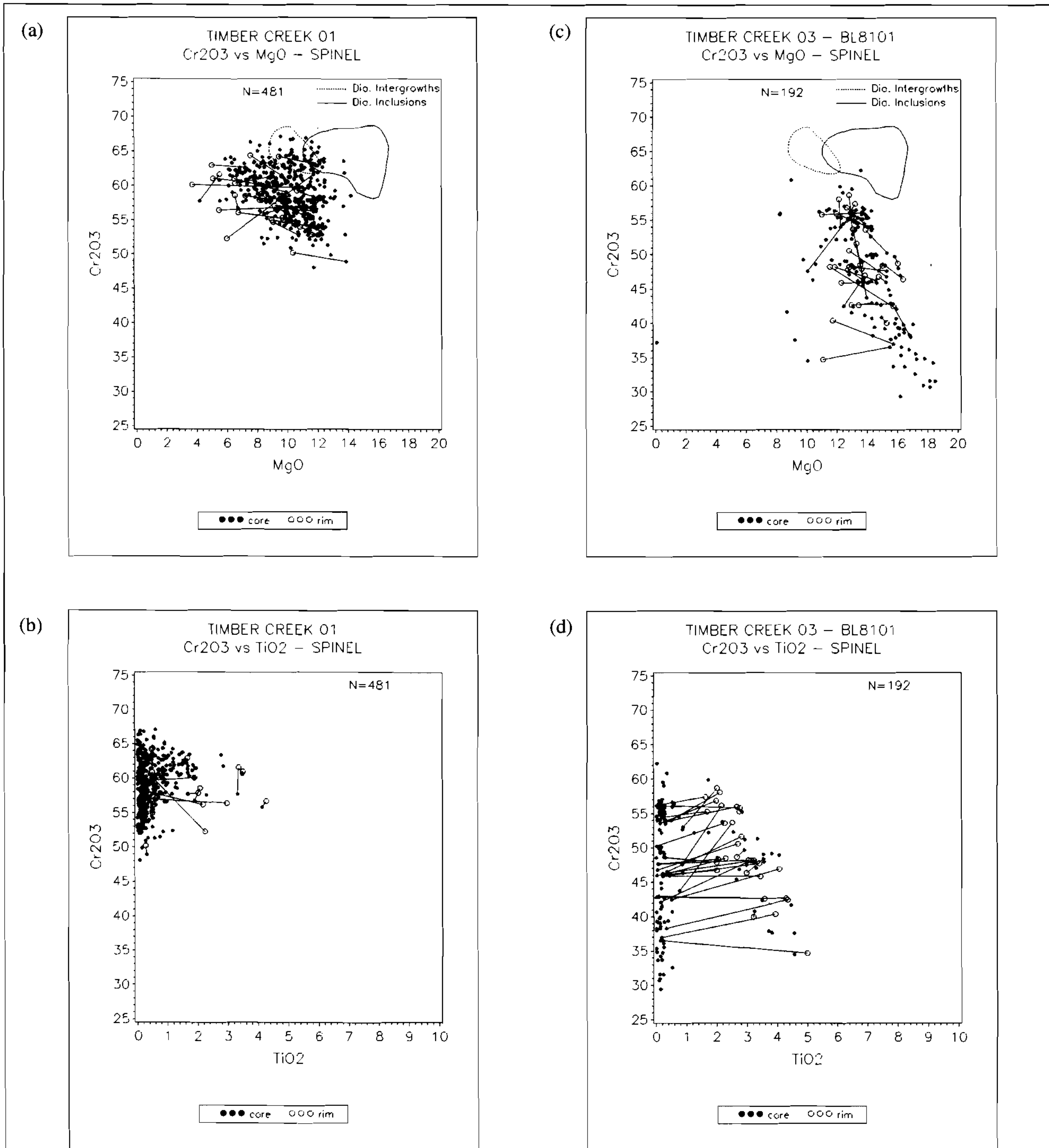

Figure 3. a, b, Cr_2O_3 - MgO and Cr_2O_3 - TiO_2 relationships for TC-01 heavy mineral concentrates c, d, Cr_2O_3 - MgO and Cr_2O_3 - TiO_2 relationships for TC-03 heavy mineral concentrates. (Diamond intergrowth and inclusion fields after Fipke *et al.*, 1995).

Zircons

Cathodoluminescence (CL) microscopy and laser ablation ICPMS analysis have been used to study the internal structure and chemical composition of zircon grains from the Timber Creek kimberlite. The grains examined were recovered from a large sample collected down slope from TC-01, and are characterised by an almost complete absence of crystal faces. They are typically rounded to sub-rounded, and display a large range of violet, pink, yellow, orange and grey colours. The grain size ranges from 1 to 2 mm, typical of mantle-derived zircons. Zircons were not recovered from heavy mineral samples collected during initial prospecting, primarily due to the scarcity of -1.0mm grains within the kimberlite.

Under cathodoluminescence (CL) the zircons are bluish, yellow and pink, with bluish hues predominating (Table 2). Previous studies (Belousova *et al.,* 1998a, b) indicate that bluish

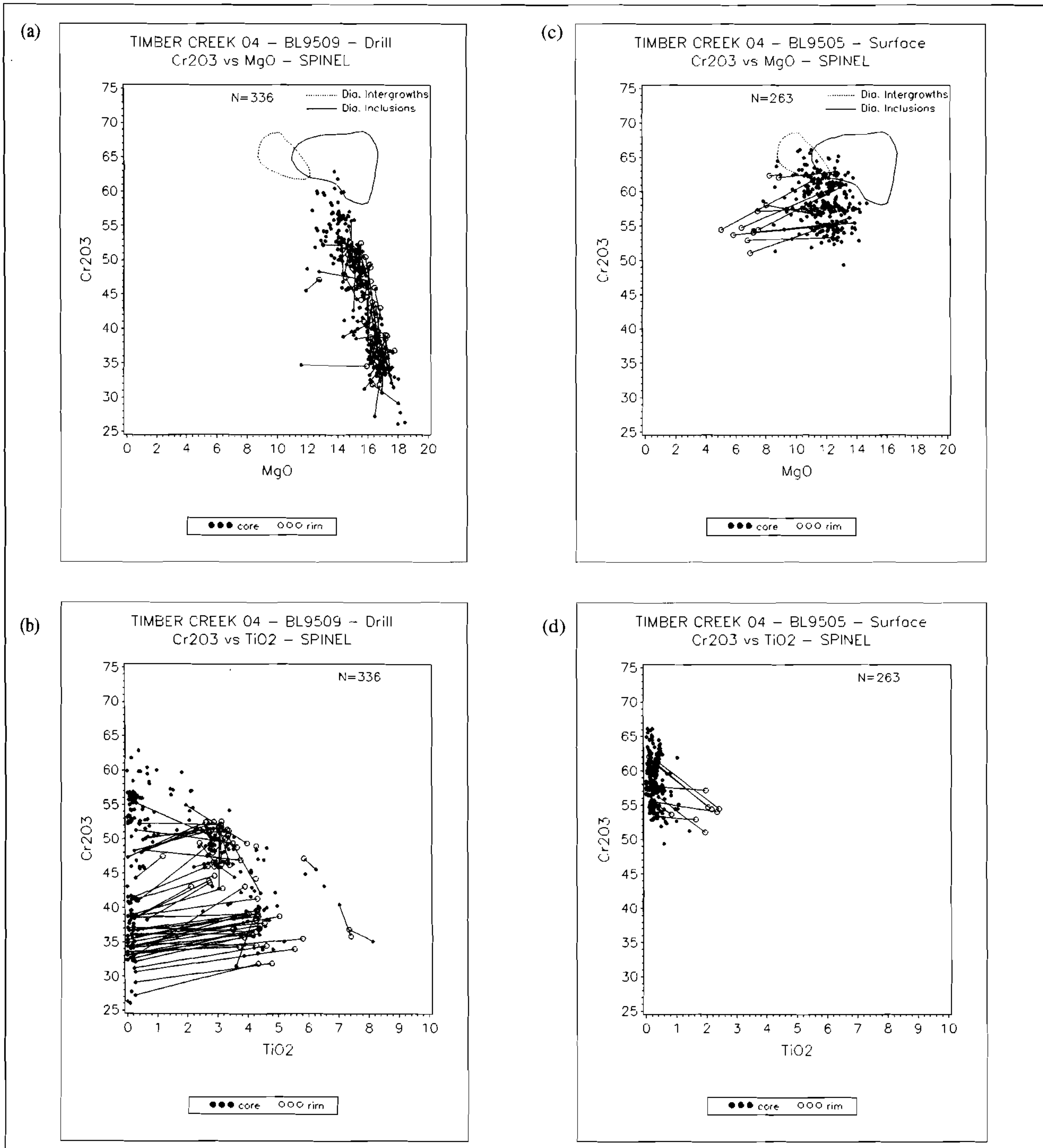

Figure 4. a, b, Cr_2O_3 - MgO and Cr_2O_3 - TiO_2 relationships for TC-04 drill sample heavy mineral concentrates. c, d, Cr_2O_3 - MgO and Cr_2O_3 - TiO_2 relationships for TC-04 surface sample heavy mineral concentrates (Diamond intergrowth and inclusion fields after Fipke *et al.*, 1995)

cathodoluminescence is typical of kimberlitic zircons and reflects low U and REE contents. Many of the zircons show zoning patterns that vary from thin oscillatory zones to broad, commonly irregular bands (Table 2). No correlation between colours observed under visible light and under the cathode beam has been found.

Timber Creek LAM-ICPMS data (Table 3) fall within the range defined for kimberlitic zircons (Fig. 5) from southern Africa, Yakutia and Australia (Belousova *et al.*, 1998b), but have very low concentrations of all trace elements and thus plot almost at the bottom of the kimberlitic zircon band. The total REE content of Timber Creek zircons is 12 ppm on average (usually Σ REE < 50 ppm for kimberlitic zircons). They also show very low U and Th values (8 ppm ± 3.6 and 4 ppm ± 2 respectively), while the more common range for kimberlitic zircons is from 10 to 30 ppm U and from 3 to 8 ppm Th. No particular correlation between trace element composition and CL colours has been found for the zircons.

Kimberlitic zircons from many localities form a distinctive field on a plot of Hf versus Y (Fig. 6) relative to the fields for zircons from other rock types (Shnyukov *et al.*, 1997), and are located well off the main trend defined by crustal zircons. The Timber Creek zircon field shows good agreement with the main field of kimberlitic zircons from other localities, overlapping mainly with the field of southern African kimberlitic zircons.

8. GEOCHEMISTRY

The highly silicified nature of the kimberlites and the relative proportion of crustal xenoliths at Timber Creek has created considerable whole rock geochemical variation, both between kimberlites and within the kimberlites at varying depths. Despite the silicified nature of the kimberlites a number of the key indicator trace elements are anomalously high and consistent with known kimberlitic values. Major trace elements such as Cr and Ni, which are usually elevated in ultrabasic rocks, are both significant in TC-02, 04 and 05, as are minor kimberlitic pathfinders such as Nb, Zr and Sr. The highly silicified nature of TC-03 has produced an unusual Ni, Cr, Co, Nb and Zr- poor composition coupled with extreme enrichment in Ba. Likewise, the TC-01 surface sample is almost completely silicified, but has minor Cr enrichment, and slightly elevated Pb. TC-05 is the least altered of the kimberlites and as such has the most typical kimberlitic enrichment.

Table 2. Results of Cathodoluminescence Observation for Kimberlitic Zircons from Timber Creek.

Grain #	Colour		Zoning	
	in usual light	Under CL	shape	CL colour
1	Violet	yellowish-bluish	sectors	yellowish, bluish
2	Violet	yellowish-pink	block	blue
			oscillatory	yellowish-pink
3	Violet	violet & yellowish	block	violet & yellowish
4	Violet	violet	irregular	yellowish
5	Violet	pinkish-blue		
6	Pink	yellowish-pink		
7	Pink	pinkish-blue		
8	Pink	violet	broad bands	yellowish-blue
9	Pink	yellowish-pink	weak oscillatory	yellowish-pink
10	Pink	violet	broad band	yellow
11	Yellow	light violet	sector	dark violet
12	Yellow	grey-yellow		
13	Yellow	violet	rim	yellow
14	Yellow	yellowish-violet	oscillatory	bright violet
15	Yellow	dark violet	broad bands	light violet
16	Orange	violet	broad band	dark violet
17	Orange	yellow	irregular	blue
18	Orange	yellowish-blue		
19	Orange	yellowish-blue	oscillatory	yellowish-blue
20	Orange	yellowish		
21	Grey	bright blue		
22	Grey	blue	rim	yellow
23	Grey	lemon yellow	weak oscillatory	yellow
24	Grey	yellowish-blue		
25	Grey	pinkish-violet		

9. DIAMONDS

Diamonds have been recovered from kimberlites TC-01, 02 and 04. Diamond recovery has not been attempted for the other two kimberlites, although chromian spinel chemistry would suggest that they have either very low diamond grades or are barren. Preliminary analysis of TC-01 suggests that it has a grade in excess of 100 CPHT. No diamonds were discovered in stream prospecting samples, although some were recovered in soil samples close to both TC-01 and TC-04.

One hundred and ten (110) diamonds recovered from loam samples over the TC-01 kimberlite were studied in detail. The diamonds are small and range in weight from 0.0016 carats to 0.0023 carats. Eighty-seven percent (87%) are well-resorbed tetrahexahedroida (rounded dodecahedra) with minor proportions of octahedra (4.5%). The remaining stones are fragments. The tetrahexahedroid form of diamond is more common in

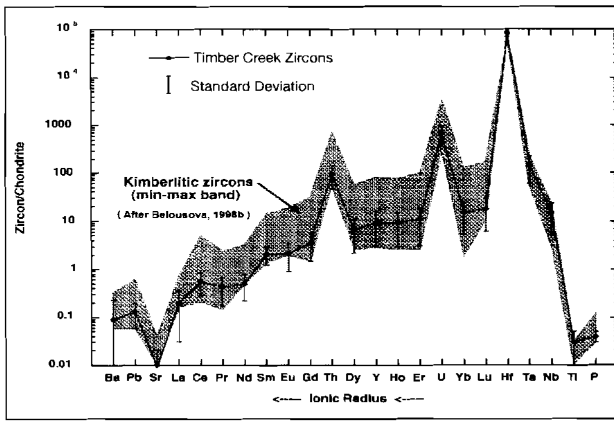

Figure 5. Trace element LAM-ICPMS data for Timber Creek zircons.

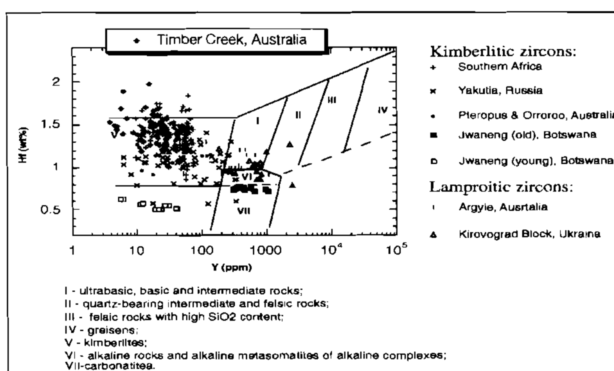

Figure 6. Hf-Y- relationships for kimberlites from South Africa, Yakutia and Australia (after Shnyukov *et al.*,1997).

Table 3. Trace element data (ppm) for zircons from Timber Creek kimberlites

"Grain*,**"	CL colour	P	Ti	Mn	Fe	Ga	Sr	Y	Nb	Sn	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Dy	Ho	Er	Yb	Lu	Hf	Ta	Pb	Th	U
1-V-t	yellowish	61	8.8	<0.13	<6.79	<0.09	0.10	4.9	6.9	0.31	1.26	<0.02	0.26	<0.03	<0.17	<0.18	0.08	<0.18	0.64	0.16	0.72	0.80	0.12	14300	4.2	0.30	2.6	6.1
1-V-b	bluish	70	54.7	<0.13	<6.93	<0.09	0.09	71.0	8.0	0.45	<0.03	0.04	0.92	0.04	0.73	0.73	0.50	2.82	8.46	2.47	10.18	13.87	2.79	12800	4.3	0.91	10.5	15.5
2-V-t	yellowish-pink	40	8.5	<0.09	<5.00	<0.06	0.12	13.2	3.9	0.12	<0.02	<0.02	0.33	<0.02	0.31	0.27	0.14	0.68	1.66	0.46	1.82	1.76	0.47	12900	2.5	0.22	3.1	5.6
2-V-b	yellowish-pink	37	6.3	<0.16	<8.32	<0.11	0.13	16.8	4.7	0.25	0.11	0.03	0.37	<0.03	0.41	0.46	<0.05	0.97	1.42	0.75	2.49	3.26	0.57	15000	2.6	0.50	4.7	7.9
3-V-t	violet	57	36.4	<0.17	<9.03	<0.12	<0.05	7.0	5.9	<0.16	0.20	0.07	0.27	<0.04	<0.22	0.42	<0.06	0.46	1.01	0.32	0.99	2.18	0.33	15700	4.5	<0.15	1.8	3.6
3-V-b	yellowish-pink	50	14.5	<0.26	<13.91	<0.18	0.15	18.3	6.0	0.30	0.07	<0.05	1.03	0.10	0.50	0.57	0.15	0.94	2.52	0.63	2.26	3.26	0.63	14800	3.1	0.36	3.0	5.4
4-V-t	yellowish	54	17.5	<0.14	<7.41	0.15	0.09	26.8	5.4	0.24	<0.04	<0.03	0.53	<0.03	0.75	0.70	0.26	1.22	3.60	0.95	4.31	5.60	1.05	14000	3.9	0.29	5.1	7.2
4-V-b	violet	50	25.2	<0.17	25.53	<0.12	0.14	6.2	5.0	0.20	0.21	0.06	0.37	<0.04	<0.23	0.53	0.07	0.42	0.96	0.22	0.51	0.91	0.24	13800	3.2	0.42	1.8	3.7
5-V-t	pinkish-blue	43	15.0	0.27	<8.72	<0.11	0.13	13.5	4.8	<0.15	0.05	0.19	0.43	<0.03	0.33	0.68	0.12	1.38	1.75	0.57	1.41	3.19	0.56	17000	3.4	0.64	3.1	6.8
5-V-b	pinkish-blue	50	12.3	0.19	<9.16	<0.12	0.18	15.8	5.3	0.36	<0.04	<0.03	0.39	<0.04	<0.22	0.33	0.25	1.12	1.79	0.61	1.45	2.33	0.53	19700	3.9	0.74	4.4	8.7
6-P-t	yellowish-pink	41	18.5	<0.11	<5.64	0.10	0.09	26.9	4.7	0.25	<0.03	<0.02	0.37	<0.02	0.14	0.70	0.10	1.20	3.89	0.83	3.58	4.58	0.83	12600	3.5	0.55	4.0	6.7
6-P-b	yellowish-pink	43	17.5	<0.12	<6.27	<0.08	0.08	29.8	5.2	0.25	<0.03	0.03	0.38	<0.03	0.33	<0.16	0.20	1.02	3.37	1.10	3.79	5.04	0.89	13700	3.5	0.53	4.5	7.7
7-P	pinkish-blue	55	45.0	<0.12	6.87	<0.08	0.14	29.6	5.1	0.36	0.04	0.06	0.55	0.06	0.79	0.63	0.28	1.50	3.65	1.12	3.31	5.17	1.01	15750	3.6	0.27	5.2	8.7
8-P-t	yellowish-blue	64	34.1	<0.12	<6.37	<0.08	0.09	15.9	9.3	0.18	<0.03	<0.02	0.42	<0.03	<0.16	0.34	<0.04	0.77	1.70	0.62	2.11	3.67	0.54	15300	7.2	0.32	4.1	9.3
8-P-b	violet	63	53.6	<0.13	<6.93	<0.09	0.14	26.1	15.9	0.23	<0.03	0.03	0.71	<0.03	0.23	0.53	0.14	1.07	2.42	0.89	3.66	4.44	0.88	14800	7.8	1.12	8.2	14.6
9-P	yellowish-pink	58	15.2	0.25	<5.76	<0.15	0.11	22.6	6.2	0.20	0.07	<0.03	0.37	0.06	<0.16	<0.24	0.22	1.13	2.61	0.80	3.20	2.97	0.93	15100	3.7	0.76	5.4	8.4
10-P-t	violet	42	21.1	0.14	7.81	0.15	0.11	20.4	4.8	0.27	0.06	<0.03	0.44	0.06	0.17	0.31	0.10	1.09	2.06	0.81	2.20	4.24	0.67	13600	2.9	1.04	5.1	8.1
10-P-b	yellow	59	48.7	<0.12	7.17	0.20	0.11	24.6	4.4	0.42	0.12	0.04	0.57	0.05	0.37	0.88	0.22	1.43	3.50	0.97	2.87	4.24	0.96	15400	1.9	0.49	5.1	7.2
11-Y-t	light violet	69	15.8	<0.13	262.08	0.45	0.21	26.4	2.7	<0.10	0.29	0.05	0.99	0.05	<0.14	0.41	0.09	1.26	2.88	0.93	2.64	4.15	0.96	11700	3.2	0.61	4.0	11.8
11-Y-b	dark violet	82	16.4	<0.17	12.72	<0.16	<0.04	10.5	1.8	0.24	<0.06	0.17	0.93	0.09	0.40	<0.26	0.18	0.35	1.89	0.50	1.14	2.22	0.40	13700	2.8	0.41	3.1	9.7
12-Y-b	greish-yellow	41	9.0	<0.07	2.87	<0.07	0.07	47.5	1.6	0.21	<0.02	<0.01	0.94	0.18	0.70	0.67	0.41	2.85	6.43	1.54	5.07	6.76	1.29	10800	1.8	<0.06	6.8	11.5
13-Y	violet	66	8.9	<0.13	<5.11	<0.13	<0.03	19.9	1.6	0.14	<0.05	<0.03	0.80	<0.02	0.16	0.21	0.09	0.74	2.80	0.63	2.22	4.23	0.68	12600	1.7	0.15	2.6	8.2
14-Y-t	yellowish-violet	60	19.3	0.12	<3.68	<0.09	0.09	40.0	2.4	0.35	<0.03	<0.02	1.02	0.04	0.53	0.41	0.43	2.78	4.74	1.44	5.37	5.98	1.31	11900	2.8	0.16	6.2	13.3
14-Y-b	yellowish-violet	47	12.7	0.23	<5.24	<0.13	0.09	31.2	1.9	0.31	<0.05	<0.03	1.03	0.10	0.38	0.81	0.13	1.55	3.73	0.85	4.36	4.02	0.61	10000	2.0	0.27	4.9	10.7
15-Y-t	dark violet	57	12.8	0.19	<5.46	<0.14	0.21	27.3	1.6	0.27	<0.05	<0.03	0.77	0.04	<0.15	<0.23	0.15	1.29	3.38	0.77	3.95	5.35	1.05	12800	2.1	0.13	4.0	10.7
15-Y-b	light violet	71	12.0	0.31	10.24	0.16	0.06	31.3	2.3	0.54	<0.05	0.04	0.87	<0.02	<0.15	0.25	0.28	1.20	3.47	1.29	4.92	5.11	1.13	13400	2.8	<0.13	6.1	17.8
16-O-t	light violet	71	31.1	0.19	7.95	0.13	0.05	12.2	7.7	0.51	<0.04	<0.03	0.27	0.03	<0.12	0.47	<0.06	0.48	0.79	0.40	1.64	2.42	0.26	14300	6.3	0.34	2.4	4.5
16-O-b	dark violet	94	52.9	<0.13	<4.84	<0.12	0.07	49.5	20.9	0.32	<0.04	0.04	0.66	<0.02	0.20	0.20	0.19	1.63	5.49	2.00	6.56	7.18	1.17	14900	14.8	1.14	9.6	17.4
17-O-t	yellow	51	14.8	0.12	<4.03	<0.10	0.03	28.3	4.6	0.18	0.13	<0.02	0.34	0.05	0.31	<0.17	0.10	1.02	3.15	1.03	3.81	3.92	0.99	13100	3.5	0.37	4.1	7.5
17-O-b	blue?	47	16.5	0.27	<4.11	0.17	0.14	15.9	5.6	0.16	<0.04	<0.02	0.35	<0.02	0.24	<0.17	0.16	0.82	1.55	0.46	2.08	3.24	0.75	12500	3.4	0.37	2.3	4.7
18-O-t	yellowish-blue	56	17.6	<0.09	9.59	0.20	0.08	8.9	6.4	0.18	0.06	<0.04	0.33	<0.02	0.34	<0.21	<0.05	<0.12	1.08	0.22	0.98	1.60	0.23	14100	4.4	0.22	2.4	5.0
19-O-t	yellowish-blue	38	14.2	<0.07	289.60	0.16	0.06	16.1	3.9	0.31	<0.04	<0.03	0.37	0.02	0.14	<0.17	0.08	0.64	1.83	0.55	2.42	3.42	0.48	14700	2.7	0.09	2.5	5.8
19-O-b	yellowish-blue	29	11.2	0.13	<3.60	0.11	0.07	11.7	3.2	0.14	<0.03	<0.02	0.34	0.06	0.12	<0.15	<0.04	0.18	1.19	0.36	1.28	2.83	0.36	11700	2.3	0.17	2.0	5.1
20-O-t	yellowish	60	24.4	0.42	<7.61	0.82	0.92	6.1	5.7	0.21	1.91	0.07	0.43	0.04	<0.24	<0.31	0.16	<0.19	1.50	0.26	0.38	<0.32	0.49	18800	3.9	0.54	2.5	5.0
20-O-b	yellowish	41	12.1	<0.12	10.34	0.17	0.07	5.1	4.4	<0.13	0.08	0.05	0.27	0.03	<0.22	<0.28	<0.07	<0.17	0.73	0.30	0.53	1.27	0.25	14800	2.5	0.32	1.7	4.6
21-G	bright blue	58	20.7	<0.13	<7.57	0.18	0.35	4.5	5.8	0.56	0.33	0.22	0.16	0.05	<0.24	<0.31	<0.08	<0.18	0.62	0.15	0.56	0.93	0.17	14900	4.8	0.39	1.9	5.4
22-G	blue	53	11.9	<0.13	32.72	0.13	<0.06	3.9	7.2	0.53	0.12	<0.06	0.34	<0.02	<0.25	<0.33	<0.08	0.41	<0.26	0.14	0.49	1.21	0.18	15200	5.1	<0.15	1.7	4.7
23-G-t	lemon yellow	37	12.2	<0.08	<4.76	0.09	0.03	21.5	5.4	<0.09	<0.04	<0.03	0.69	<0.02	0.31	0.25	0.17	1.16	2.37	0.91	3.45	3.65	0.59	16700	3.4	0.69	4.7	8.3
23-G-b	lemon yellow	40	11.8	0.24	<6.49	<0.10	0.15	17.9	5.3	0.21	0.20	<0.04	0.25	0.04	<0.21	<0.26	<0.07	0.73	1.51	0.80	2.20	2.48	0.61	16200	3.4	0.31	4.1	7.5
24-G	yellowish-blue	54	10.3	4.19	<7.83	<0.13	0.06	5.8	5.9	<0.15	<0.07	<0.05	0.37	<0.03	<0.25	<0.32	<0.08	0.50	0.35	0.13	0.93	0.37	0.26	16850	4.4	0.57	2.1	4.7
25-G	pinkish-violet	31	22.3	<0.06	<3.30	0.13	0.09	18.5	4.6	0.24	<0.03	<0.02	0.36	0.04	0.12	0.29	0.12	1.19	2.11	0.76	2.43	3.39	0.65	16500	3.0	0.53	3.2	6.3
Average		53	20.6	0.48	52.73	0.21	0.13	20.7	5.5	0.29	0.30	0.07	0.53	0.06	0.36	0.48	0.19	1.11	2.52	0.75	2.69	3.68	0.70	14351	3.8	0.47	4.1	8.1
StDev		14	13.3	1.03	99.51	0.18	0.14	13.8	3.5	0.12	0.49	0.06	0.26	0.03	0.20	0.20	0.11	0.64	1.67	0.49	1.93	2.33	0.47	1978	2.2	0.27	2.1	3.6

* Colour of the grain (usual light):
" V- violet, P- pink, Y- yellow, O- orange, G- grey."

** Part of the grain analysed:
" t - top, b - bottom,"

samples representing hypabyssal-facies dykes and root zones than in samples from diatreme facies (Robinson *et al.*, 1989). The high incidence of resorbed diamonds in TC-01 correlates with the root zone character of this body. Sixty percent (60%) of the diamonds are macles.

The diamonds are predominantly brown to yellow in colour (brown 16%, pale brown 35%, brown/yellow 15% and yellow/pale yellow 20%). Brown diamonds are frequently associated with lamination lines on dodecahedral surfaces and are thought to be due to plastic deformation (followed by resorption) at temperatures above 1000°C (Robinson *et al.*, 1989). Twenty-one percent (21%) of the TC-01 diamonds have lamination lines, and this, together with the abundance of brown stones suggest that they were deformed while still in the upper mantle.

Forty percent of the diamonds have green radiation damage spots, particularly within deep cracks or ruts. Similar green spots have been noted in old (>800Ma) kimberlites such as Aries (Towie *et al.*, 1994) and the Forrest River area of northern Western Australia (Wyatt *et al.*, 1998). A high proportion (49%) of the stones has surface ruts. Most ruts trace octahedral to sub-conchoidal planes on tetrahexahedroid surfaces. Robinson *et al.* (1989) suggest that ruts represent either planer zones of weakness or actual cracks widened by resorption or etching. Most of the diamonds contain small unidentified opaque mineral inclusions; these are possibly sulphides, chromium-rich spinels or graphite. In most cases the diamonds are too small for detailed inclusion studies. In conclusion, the features on diamonds from TC-01 are consistent with plastic deformation in the upper mantle followed by extensive resorption by hot hypabyssal-facies kimberlite magma during emplacement. The resorption and deformation features of the diamonds are believed to weaken the structure of the stones to the point that very few diamonds are recovered any distance from the kimberlite surface exposures.

Table 4. Whole Rock Chemical Analysis of Timber Creek Kimberlites.

ELEMENT	TC-01 (I)	TC-01 (II)	TC-02(I)	TC-03(I)	TC-04 (I)	TC-05(II)
SiO_2	91.64	51.55	54.92	93.81	73.17	20.34
TiO_2	0.28	1.89	2.91	0.32	2.86	4.09
Al_2O_3	2.48	14.98	5.45	1.92	6.46	8.75
Fe_2O_3	2.19	17.14	10.45	1.7	13.76	8.46
MnO	0.02	0.02	0.29	0.19	0.26	0.13
MgO	0.70	6.12	12.85	1.8	1.56	29.83
CaO	0.67	2.48	11.52	0.13	0.31	25.13
Na_2O	0.23	0	0	0	0	0
K_2O	0.53	3.57	0.26	0.09	0.81	0.14
P_2O_5	1.38	1.71	0.82	0.06	0.18	2.23
TOTAL	100.27	99.47	99.46	100.05	99.37	99.1
L.O.I.		6.01	16.88	2.15	4.16	29.04
V	44	140.7	166.4	40.2	113.5	196.1
Cr	342	2072	1801	476	2432	1552
Co	-5	30	45	27	26	24
Ni	33	986	958	449	495	394
Cu	50	0	12.5	6.9	38.3	15.5
Zn	37	53	62	9.1	65.4	44.4
As	-3	4	4	0	7	9
Se	0	35.8	32.5	6.4	25.1	38.8
Rb	30	224	14.5	4.7	94	7.3
Sr	12	43	67.9	15	19.8	345
Y	9	66	25.1	15.7	44.8	67.7
Zr	85	549	401	63.7	415	553
Nb	62	201	168	18.2	186	286
Ba	187	240	400	520	802	3008
La		106	84.3	55.5	31.3	222
Ce		207	171	37	92	371
Nd		92	72	31	34	166
S		0	67	0	109	1479
Ga		18	7	3	15	10
Pb	29	8	7	2	7	9
Th	6	41	13.5	4.9	21	22.3
U	2	8.6	2.5	0.5	6.4	4.9

(I) Surface sample, (II) Drill Sample

10. CONCLUSIONS

The five Group 1 hypabyssal facies kimberlites discovered in the Timber Creek area of the Northern Territory are the first rock types of this kind discovered within the Proterozoic Victoria River Basin. The kimberlites were found following the recovery of chromian spinel in heavy mineral stream sediment samples. The kimberlites are heavily silicified and are poorly exposed. TC-01 is a small pipe, whereas the remaining four kimberlites are dykes, striking at approximately 300°.

TC-01 and TC-04 contain a significant proportion of diamond inclusion type spinels, and have estimated diamond grades in excess of 100 CPHT. The diamonds are predominantly yellow or brown, and contain deep ruts, suggestive of substantial resorption. The diamonds have not been found a significant distance from kimberlite exposure. The spinel grains are particularly brittle and also only survive minimal transportation. LA-ICPMS data and cathodoluminescence studies show that the Timber Creek zircons have cathodoluminescence properties and trace element contents similar to those of kimberlitic zircons from Southern Africa, Yakutia and Australia. The age of kimberlite emplacement is ambiguous, but is most likely between 1000Ma and 1500Ma. Ion microprobe (SHRIMP) dating of Timber Creek zircons yields a mean $^{206}Pb/^{238}U$ age of 1462 ± 53Ma and Fission Track analyses yield a mean age of 1038 ± 66Ma.

The kimberlites are significant because they confirm the prospectivity of the North Australian Craton, the VRB in particular, and because they indicate that the VRB is probably older than initial basin correlation and dating have previously suggested.

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