ARCHAEAN ZIRCON XENOCRYSTS FROM THE JWANENG KIMBERLITE PIPE, BOTSWANA.

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INTRODUCTION

U-Pb ages of kimberlitic zircon were first obtained by Davis *et al.*, 1976. Results compiled subsequently from over 20 localities in and around the Kaapvaal craton of southern Africa, and others from Brazil (Davis, 1977), all gave ages in the range 94 - 52 Ma, close to the known ages of pipe emplacement as determined by other methods. Davis recognised that as xenocrysts the zircons could be much older than their indicated ages,but might not have retained radiogenic Pb until the temperature dropped in the rising kimberlitic magma prior to eruption. We present here the results of U-Pb dating by ion microprobe of zircons from the Jwaneng pipe in Botswana which show that some zircons have in fact preserved Precambrian ages, although the pipe was emplaced in the late Permian. Two distinct age populations are present, hereafter termed the "old" and "young" zircons. The results are confirmed independently by hafnium model ages measured on the same grains with the ion microprobe, providing direct evidence for the occurrence of deep-seated nodules of Archaean age in the mantle source regions of the Jwaneng kimberlite, as well as others which formed close to the time eruption.

THE JWANENG ZIRCONS

The Jwaneng zircons are typical of those previously described from kimberlites which are believed to be xenocrysts associated with the deep-seated suite of discrete nodules (Kresten *et al.*, 1975). They are rounded megacrysts up to 3mm in diameter with minor surface pitting. Colours range from colourless to honey brown or orange hues. Viewed in section, the crystals show no internal structure other than for an abundance of platy and acicular inclusions (rarely over 60µm in length) some of which have been identified as apatite, and, in some instances, fluid inclusions. One grain in particular, J2 9, contains networks and droplets of liquid inclusions of the type illustrated in Kresten *et al.*, 1975, p50. Their alignment in discrete arcuate planes within the crystal indicates a secondary origin related to fracture annealing.

The two age groups are morphologically indistinguishable, but can be identified by differences in their trace element compositions. All grains are typically trace element-poor; low U and Th abundances in particular are consistent with the findings of Ahrens *et al.*, 1967 and later workers. However, as shown in Figure 1, the young grains are markedly richer in U than the old grains and with Th/U averaging 0.2 as compared with values typically in the range 0.4 - 0.5. Additionally, the young grains are considerably poorer in Hf and heavy REE, and higher in Ta content. The latter was identified with the ion-probe during Hf isotopic analyses as present in the zircons in unusually high abundances, though still below detection limits of the CAMECA electron-probe at ANU (~ 100 ppm for Ta).
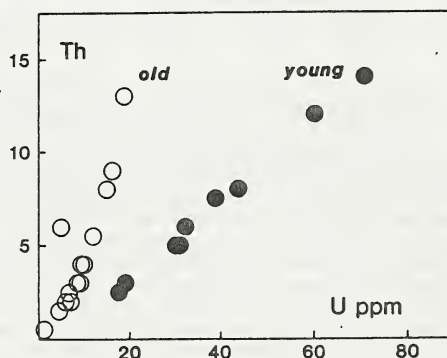

Figure 1: Plot of U vs Th contents of zircons from the Jwaneng kimberlite.

ANALYTICAL METHODS

Fifteen grains selected at random were broken, and fragments mounted in two epoxy discs (J1 and J2) which were polished and a conductive coating applied to their surface. No other prior treatment of samples is required for isotopic analysis by ion microprobe, in which material for analysis is sputtered from an exposed 25µm area within a crystal by a focused beam of oxygen ions. The routine for U-Pb analyses by the ANU ion microprobe SHRIMP has been described in detail by Compston *et al.*, 1984, and in subsequent publications, however the techniques employed for hafnium isotopic analyses have not yet been described. Briefly, Hf isotopes are measured on the electron multiplier as HfO^+ species. Reduced ratios are corrected for isobaric interferences of YbO, LuO and HfOH, and for mass fractionation by normalizing standard Hf isotopic ratios to values determined by thermal ionization mass spectrometry (Patchett, 1983).

RESULTS

Young zircons : For young zircons which are low in radiogenic ^{207}Pb, the measured $^{207}Pb/^{206}Pb$ yields a very imprecise estimate of age. On average, 74% of the total ^{207}Pb measured in the young Jwaneng zircons was non-radiogenic , as compared with 19% of the total ^{206}Pb. The $^{206}Pb/^{238}U$ age of these grains is consequently the most reliable. The results of the ion-probe U-Pb analyses of nine young grains are given in the lower part of Table 1. Seven of these gave values of $^{206}Pb*/^{238}U$ (* radiogenic) which are equal to within the analytical uncertainties. The

weighted mean value, 0.03720 ± 2 (1σ), corresponds to an age of 235 ± 2 Ma. This result is very close to a Rb-Sr mica age of *ca.* 242 Ma (J.W.Bristow, unpubl. data) for a small satellite pipe adjacent to the main DK2 pipe at Jwaneng from which the zircons were derived. It suggests that the Jwaneng kimberlites were emplaced at 235 Ma or soon after. The remaining two grains, J2 1 and J2 6, gave younger ^{206}Pb/^{238}U ages of 223 ± 3 and 218 ± 3 Ma

respectively (both 1σ). We interpret these results as indicating that those two grains lost a small portion of their accumulated radiogenic Pb recently. The possibility that all of the grains have leaked a little Pb since their time of formation must be considered, because it would imply that 235 ± 2 Ma is not strictly a maximum age for the pipe even if the zircons are xenocrysts. Since the locus of Pb loss from young zircons is approximately parallel with the Concordia curve, the extent to which this may have occurred cannot be determined. However, in this case the effects are probably minor, given the similarity between the majority of zircon ^{206}Pb/^{238}U ages and the mica age.
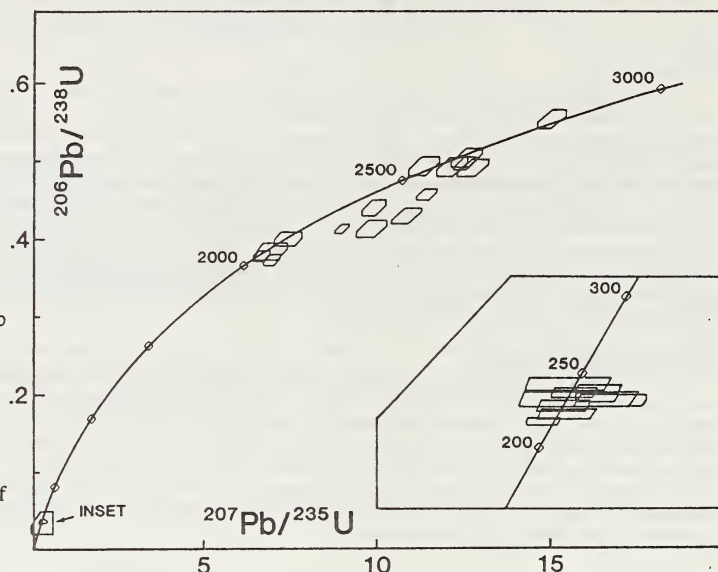
Figure 2: Concordia diagram showing results of U-Pb isotopic analyses of Jwaneng zircons. Error limits, as per Table 1, are 1σ.

Old zircons : Of the fifteen grains analysed, six have preserved much older Pb/Pb and U-Pb ages than those described above, confirming their xenocrystic origin. In order to investigate the extent of any internal isotopic variation, three of the old grains were analysed at three separate locations, and one grain in five areas. The results of these analyses are listed in the upper part of Table 1, and plotted on a U-Pb Concordia diagram in Figure 2.The single analysis of Grain J2 9 has been omitted from Fig.2, because the grain contains less than 1 ppm radiogenic Pb and the analytical uncertainties are much larger than for the other grains. At least one analysed area on each grain gave concordant U-Pb ages. These ranged from 2100 to 2800 Ma. The four grains for which multiple areas were analysed showed contrasting variations in isotopic composition. Three analyses of J1 2 were equal to within error and concordant at 2135 Ma. The results for J1 3 and J2 7 included both concordant and slightly discordant analyses (plotting below the Concordia curve), consistent with closure of the U-Pb systems at 2600 and 2695 Ma respectively, followed by variable minor Pb loss either recently or at the time of pipe emplacement. In contrast, three analyses of J1 1 showed a significant range in ^{207}Pb/^{206}Pb indicating that this zircon lost Pb in ancient times, in fact as early as 1707 ± 664 Ma (based on the lower intercept with Concordia of a regression line through the three data points). These results indicate that processes causing Pb loss were operative both in the source regions of the zircon xenocrysts and, subsequently, in the pipe itself.

Hafnium data : The isotopic composition of hafnium is modified over time by the addition of ^{176}Hf from the decay of ^{176}Lu. Since Hf substitutes for Zr in the zircon lattice at the percent level, it preserves in the zircon the isotopic composition of the source environment at the time of crystallization, and is well-buffered against post-crystallization disturbances that may affect other isotopic systems. Furthermore, since kimberlitic zircons are highly depleted in REE, correction for subsequent *in situ* decay of ^{176}Lu is negligible. Four zircons from Jwaneng were analysed for Hf, two young and two old grains, and results are shown in Table 2. Whereas both old grains (J2 7 and J2 9) give Archaean Hf model ages, the young grains (J2 11 and J2 12) contain a more evolved Hf isotopic composition, consistent with relatively recent extraction from the mantle.

DISCUSSION

Considering the elevated temperatures (≥ 1100˚C) estimated for the source regions of the ilmenite-silicate nodules with which kimberlitic zircons are believed to be associated (Boyd and Nixon, 1973) the preservation of old U-Pb ages implies that the *ca* 750˚C "blocking temperature" assumed for Pb in zircons (eg Mattinson, 1978) is too

low, or that factors other than ambient temperature influence the retention capability of kimberlitic zircon for Pb. Certainly, as was pointed out by Davis (1977), the possible influence of accumulated radiation damage on Pb loss from such U-depleted crystals would be minimal.

Collectively, the U-Pb isotopic data for the old zircons are consistent with the following alternatives:

1. Original formation *ca* 2800 Ma followed by variable Pb loss during a single diffusive episode at 2100 Ma,

2. Formation of different grains at discrete times between 2800 and 2100 Ma, or

3. Formation of all grains prior to 2800 Ma, with the observed array of nearly-concordant U-Pb ages in different grains reflecting different times at which they began to retain radiogenic Pb. The last best explains the Hf model ages of 3.58 ± 0.17 and 3.18 ± 0.15 Ga for J2 7 and J2 9 respectively, which are significantly older than their U-Pb ages, and which are in agreement with Archaean model Sm-Nd and Rb-Sr ages that have been measured on garnet inclusions in diamonds from southern African kimberlites (Richardson *et al.*, 1984).

In the context of previous studies it could be argued that the young zircons represent Precambrian xenocrysts whose U-Pb isotopic systems have been reset to the pipe age. However, several lines of evidence argue for a separate origin close to the time of eruption: the lack of a continuum of U-Pb isotopic compositions between the young and old grains, the differences in trace element composition, and, most conclusively, the difference in Hf isotopic composition.

Table 1: SHRIMP U-Pb isotopic analyses of zircons from the Jwaneng Kimberlite, Botswana. Isotopic ratios are corrected for common Pb (mostly surface Pb) which was determined from the measured $^{208}Pb/^{206}Pb$, the expected radiogenic $^{208}Pb/^{206}Pb$ for the measured Th/U, and assuming a common $^{208}Pb/^{206}Pb$ ratio of 2.2285 (Broken Hill Pb composition). Ages were calculated using $\lambda^{238}U = 1.55125 \times 10^{-10}$ y^{-1}, $\lambda^{235}U = 9.8485 \times 10^{-10}$ y^{-1}, and $^{238}U/^{235}U = 137.88$. 1σ errors.

Grain - spot	U ppm	Th ppm	232/238	%common 206 Pb	207/206	206/238	207/235	207/206 age [Ma]
J1 1-1	15	8	.555	5.8	.1834±34	.496±8	12.54±.32	2684±31
J1 1-2	9	3	.424	7.6	.1974±41	.553±12	15.05±.42	2805±34
J1 1-3	17	9	.592	2.2	.1586±28	.412±6	9.01±.21	2441±30
J1 2-1	9	3	.423	16.8	.1357±70	.399±9	7.47±.42	2173±90
J1 2-2	12	6	.495	8.3	.1288±39	.377±7	6.70±.25	2082±53
J1 2-3	10	4	.414	6.5	.1362±41	.372±7	6.99±.25	2180±52
J1 3-1	5	2	.435	11.5	.1736±62	.412±11	9.86±.44	2593±60
J1 3-2	7	3	.433	7.6	.1675±50	.492±12	11.36±.45	2533±50
J1 3-3	6	2	.450	8.4	.1797±50	.491±12	12.17±.45	2650±46
J1 3-4	19	13	.726	5.6	.1818±38	.456±7	11.43±.30	2669±35
J1 3-5	9	4	.505	8.0	.1641±47	.439±10	9.93±.35	2498±48
J1 5-1	5	6	1.342	12.9	.1320±79	.383±11	6.97±.49	2125±105
J2 7-1	7	2	.391	8.3	.1817±46	.503±12	12.60±.45	2668±42
J2 7-2	7	2	.389	9.7	.1890±50	.490±11	12.77±.46	2733±44
J2 7-3	7	2	.400	9.4	.1836±50	.429±10	10.86±.45	2686±45
J2 9-1	1	<1	.373	44.7	.1722±464	.586±58	13.9±4.0	2579±465

Grain - spot	U ppm	Th ppm	232/238	%common 206 Pb	207/206	206/238	207/235	206/238 age [Ma]
J1 4A-1	31	5	.180	14.2	.051±7	.0361±6	.255±39	229±4
J2 1-1	31	5	.192	21.2	.053±8	.0352±5	.259±44	223±3
J2 2-1	18	3	.169	33.0	.054±16	.0368±8	.272±88	233±5
J2 3-1	39	8	.205	12.7	.058±6	.0378±5	.304±32	239±3
J2 4-1	33	6	.190	24.6	.064±10	.0366±6	.321±52	232±4
J2 5-1	61	12	.211	13.9	.059±6	.0370±5	.301±30	234±3
J2 6-1	71	14	.207	12.1	.047±5	.0344±4	.225±25	218±3
J2 11-1	44	8	.207	16.1	.052±6	.0375±5	.270±34	237±3
J2 12-1	19	3	.179	26.1	.049±11	.0384±7	.257±67	243±4

Table 2: SHRIMP Hf isotopic analyses of zircons from the Jwaneng Kimberlite, Botswana. Uncertainties in $^{176}Hf/^{177}Hf$ and in age are the standard error, based on counting statistics. %HfO2 and Zr/Hf are from electron-probe analyses. The measured $^{176}Lu/^{177}Hf$ was calculated as $0.5 \times {}^{176}LuO^{+}/^{177}HfO^{+}$ (as observed for zircon standards). Ages were modelled on an unfractionated chondritic mantle reservoir (Patchett, 1983) using $\lambda^{176}Lu$ (β⁻) = 1.94 × 10^{-11}y^{-1}.

Grain	%HfO2	Zr/Hf	measured 176Lu/177Hf	measured 176Hf/177Hf	initial 176Hf/177Hf	model age [Ga]
J2 7	0.68	167	.00022	.28042±12	.28041	3.58±.17
J2 9	0.81	139	.00032	.28070±10	.28068	3.18±.15
J2 11	0.51	223	.00001	.28300±14	as measured	−0.20±.19
J2 12	0.60	191	.00004	.28286±13	as measured	0.01±.18

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