Appendix: Abstracts

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A fertile Palaeoproterozoic magmatic arc beneath the Central African Copperbelt

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ABSTRACT**:** Chemical characteristics and new U-Pb SHRIMP zircon age data from the basement of the Katangan Sequence in the Central African Copperbelt confirm the existence of a Palaeoproterozoic calc-alkaline volcanic arc. The Lufubu schists, comprising intermediate to acid metavolcanics, have been dated at circa 2000 Ma. Granitic gneiss from the Mkushi copper mine south of the Zambian Copperbelt yields an age of 2049 Ma, whereas the Mufulira granite in the Copperbelt is 1991 Ma. The Samba copper porphyry is dated at circa 1960 Ma. Quartzite from the Muva Supergroup, which unconformably overlies the crystalline basement, exhibits a broad range of detrital zircon ages from 3180 Ma down to 1941 Ma, indicating both Archaean and Palaeoproterozoic provenances. The basement to the world class copper-cobalt deposits of the Katangan Sequence is regarded as a magmatic arc that is, in itself, copper enriched. This has implications for ore-genesis models in the region.

1. INTRODUCTION

The Central African Copperbelt, hosted by Neoproterozoic metasediments of the Katangan Sequence, is one of the great metallogenic provinces of the world, being a leading producer of Cu and Co, as well as lesser amounts of Pb, Zn, Ge, Ga, U, Au and PGE (Master, 1998a, b). It has long been recognised that the basement to the Katangan Sequence in the Copperbelt contains abundant copper mineralization (Pienaar, 1961), and many authors have regarded this as having an important bearing on the origin of the Copperbelt ores. This pre-Katangan basement consists of schists of the Lufubu Group, which are intruded by a variety of granitoids, both of which are unconformably overlain by metaquartzites and schists of the Muva Supergroup. Whereas the granitoids have previously yielded Rb-Sr ages of between c. 2.0 to 1.8 Ga, no dating has been done on the Lufubu schists or the Muva sequence. We present here the first SHRIMP U-Pb zircon ages of the Lufubu Schists, various granitoids, and detrital zircons from the Muva quartzites.

1.1 *Regional Geological Setting*

Although the Central African Copperbelt has a strike length of 500 km in the Lufilian Arc of Katanga (D.R. Congo) and Zambia, the pre-Katangan basement is mainly exposed in the Zambian Copperbelt and in immediately adjacent areas of Katanga. About half of this basement consists of granitoids, and the rest consists mainly of Lufubu schists, with subordinate areas of Muva quartzites.

1.2 *Lufubu schists*

The Lufubu schists consist mainly of biotite or muscovite and quartz-bearing micaceous schists and quartzites, with minor or accessory plagioclase, tourmaline, sphene, zircon, calcite and pyrite. Although they were previously regarded as of meta-sedimentary origin (e.g. Mendelsohn, 1961), new geochemical results (Figs. 1 and 2) show that the Lufubu schists are calc-alkaline metavolcanics, with compositions ranging from trachyandesite to rhyo-dacite and rhyolite.

1.3 *Granitoids*

Field evidence from Mufulira and other places indicates that the schists are intruded by a variety of granitoids, which range in composition from biotite granites to quartz monzonites, granodiorites and tonalites (Mendelsohn, 1961). Previous dating of these granites has yielded imprecise ages of 2.0-1.8 Ga (Cahen et al., 1984; Ngoyi et al., 1991).

1.4 *Muva*

The Muva Supergroup unconformably overlies the Lufubu schists and includes mainly quartzites with minor argillaceous beds (Garlick, 1961).

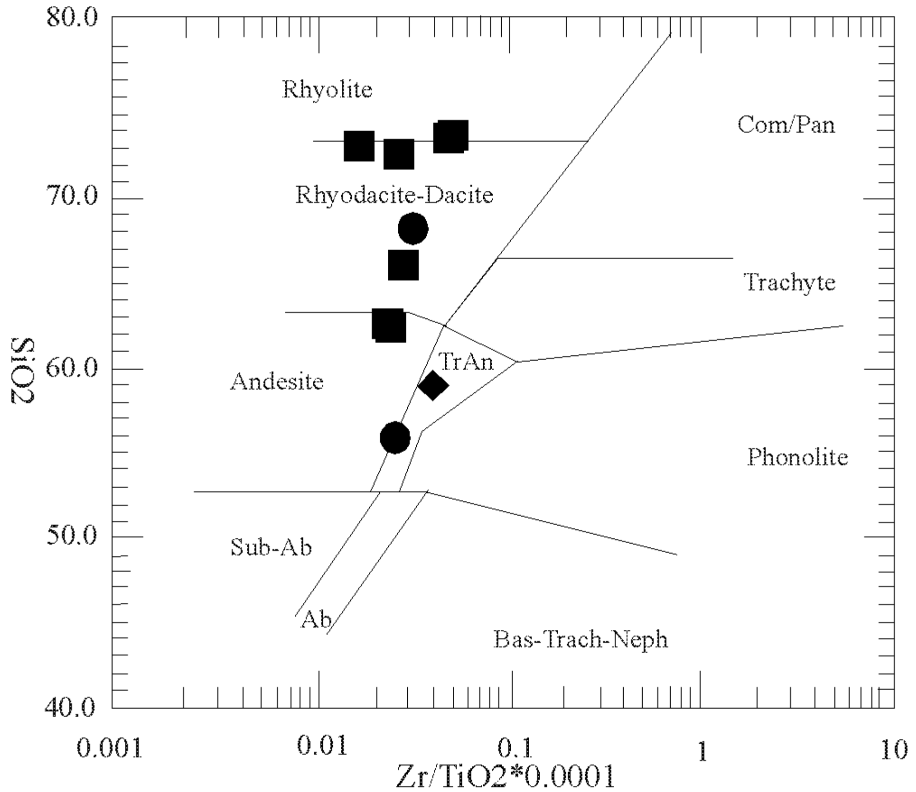

Figure 1: Lufubu schists plotted on the classification diagram of Winchester and Floyd (1977). Filled squares - Lufubu schists from Mufulira. Filled circles - Lufubu schists from Kafue River, south of Mufulira. Diamonds - Lufubu schists from Kinsenda.

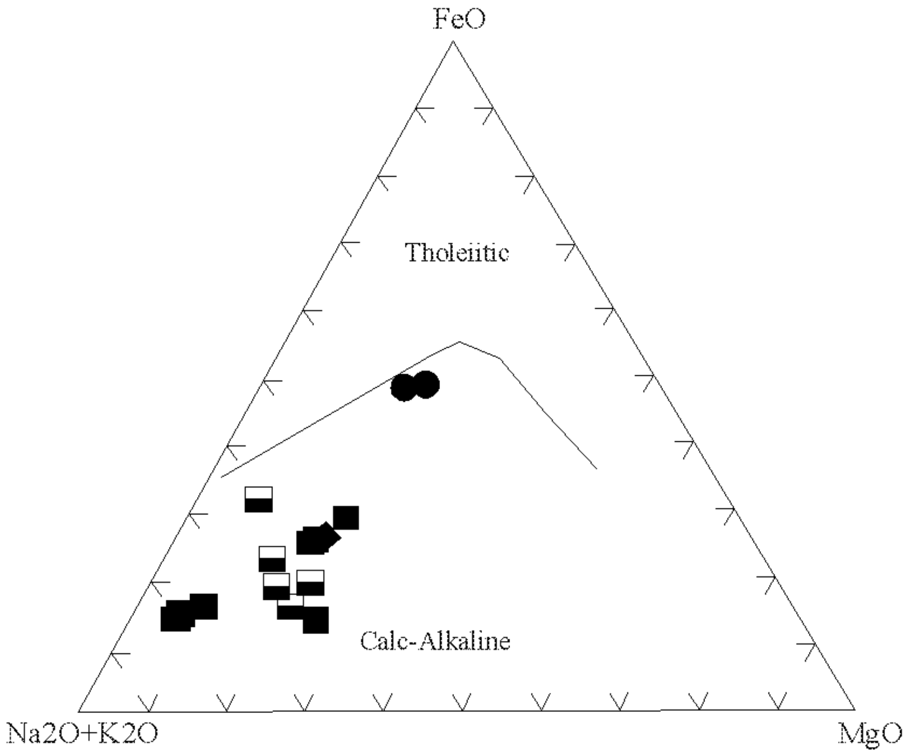

Figure 2: Lufubu schists (symbols as in Fig. 1), and host rocks of the Samba porphyry Cu deposit - half filled squares (Wakefield, 1978) plotted on the discrimination diagram of Irvine and Barager (1971), showing calc-alkaline compositional trends.

2. RESULTS

We present new zircon U-Pb ages of the Mufulira granite, the Mkushi gneisses from the Mkushi copper mine, SE of the Copperbelt (for which an earlier Rb-

Sr age of 1777 ± 89 Ma had been obtained by Ng'ambi et al., 1986) and detritus from the Muva quartzites. In addition we have age data for the Samba porphyry and a granite intersected in boreholes through the Chambishi Basin, as well as intermediate to felsic metavolcanics from the Lufubu schists.

2.1 *The Lufubu Schists*

The Lufubu schists, sampled from Kinsenda (in the DR Congo) and Mufulira (Zambia) yielded similar ages at circa 2000 Ma. The existence of material of similar age from a large sampling area indicates widespread intermediate to acidic volcanism in Central Africa.

2.2 *Granitoids*

The Mkushi gneiss yielded a weighted mean $^{207}Pb/^{206}Pb$ age of 2049 ± 6 Ma (Fig. 3) which can be interpreted as the age of emplacement of the gneiss protolith. Aplites which cut through the gneisses contain significant economic copper mineralization (now mined out), but their age has not yet been obtained.

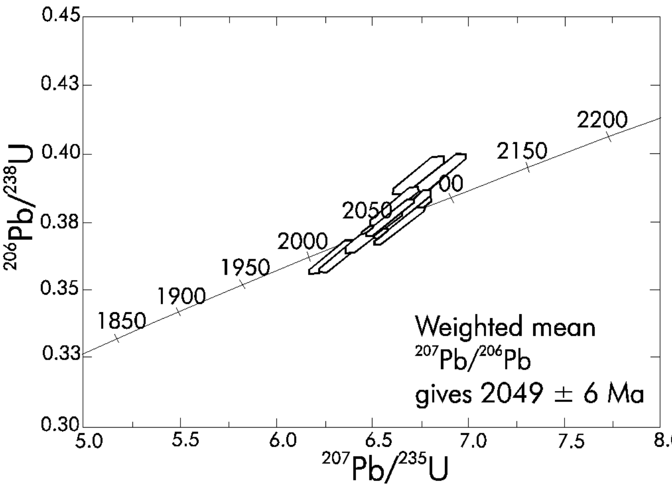

Figure 3: Concordia diagram of the Mkushi gneiss.

The Mufulira granite yielded a well-constrained age of 1991 ± 3 Ma (Fig. 4), which is considered as the age of the intrusion.

The Samba porphyry, a mineralized granite with copper ore reserves estimated at 50 million tons (Wakefield, 1978), together with a granite located beneath the Chambishi basin, yielded similar ages at circa 1960 Ma.

2.3 *Muva quartzite*

44 analyses have been carried out on 42 detrital zircons from a sample of the Muva quartzite close to Mufulira. The results are plotted on the concordia diagram in Figure 5, where it is seen that a wide range of ages exist. A significant Archaean component is observed with ages clustering at 2550 to 2700 Ma and also at around 3000 to 3180 Ma. Palaeoproterozoic zircons range down to 1941 Ma, the youngest zircon in the population and an indication, therefore, of the maximum age of deposition for the Muva Supergroup. The provenance for the Muva sediments clearly comprises both the local Palaeoproterozoic basement as well as Archaean crust.

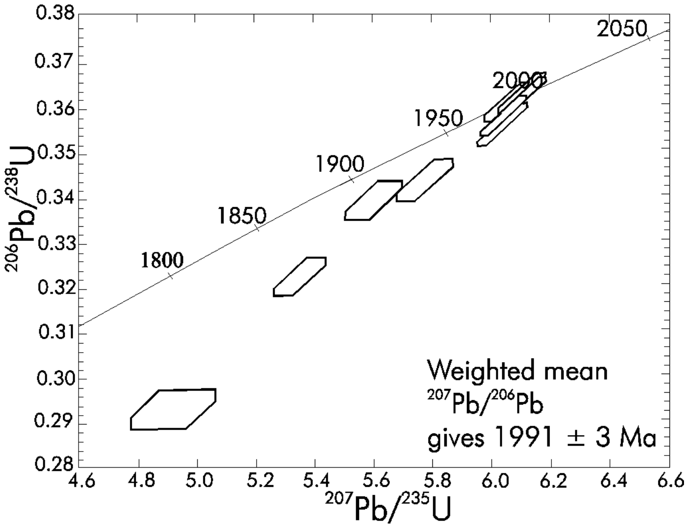

Figure 4: Concordia diagram of the Mufulira granite.

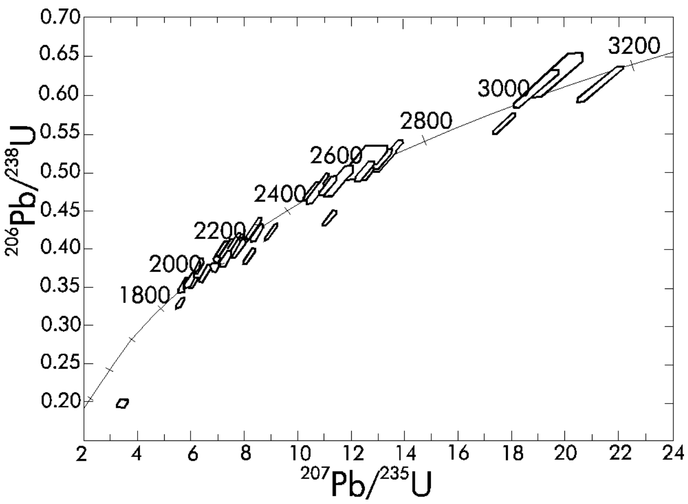

Figure 5: Concordia diagram showing ages of detrital zircons in the Muva quartzite.

3. CONCLUSIONS

The basement to the Katangan Sequence, host to the world-class Cu-Co mineralization of the Central

African Copperbelt, comprises a Palaeoproterozoic calc-alkaline magmatic arc. Tonalite-granodiorite gneisses (Mkushi) together with more evolved granitoids (Mufulira, Samba, and Chambishi) represent the plutonic phases of a major intermediate to acid volcanic province (Lufubu schists) emplaced in the range 2050 to 1950 million years ago. This basement complex is unconformably overlain by the Muva Supergroup which is younger than 1940 Ma and contains detrital zircons, the age of which indicate the presence of both Archaean and Palaeoproterozoic provenances. This basement complex is characterized by the presence of Cu mineralization in the form of the economically significant Samba porphyry copper deposit and the enigmatic aplite-related copper mineralization in the Mkushi gneisses. The basement to the Katangan Sequence is, therefore, fertile with respect to copper and this has implications for the origin and formation of the enormous metal concentrations in the latter. Ore genesis models which favour the circulation of diagenetic or metamorphic brines through permeable basal Katangan sediments, enabling fluids to interact with detrital metal-rich components derived from the fertile basement, and then re-precipitate sulphide ores at redox interfaces in the overlying sedimentary sequences (Master, 1998a) receive added impetus in the light of the data presented above.

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A cryptic Mesoarchaean terrane in the basement to the Central African Copperbelt: U-Pb evidence from detrital and xenocrystic zircons from the Muva and Katangan sequences

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Introduction

We have been engaged in a project on the geochronology of the Katangan Sequence and its basement in the Central African Copperbelt (Rainaud et al., 1999). During this study, using the SHRIMP, we have dated detrital and xenocrystic zircons from Muva quartzites and Katangan lapilli tuffs, which provide the first evidence for the existence of a Mesoarchaean basement beneath the Central African Copperbelt.

The Central African Copperbelt, hosted by the Neoproterozoic Katangan Sequence, is situated in Zambia and the Katanga Province of D.R. Congo. The Katangan Sequence, consisting mainly of metasediments with minor mafic tuffs and sills, is dated at between 880 and 620 Ma (Armstrong et al., 1999; Cahen et al., 1984). The exposed basement to the Katangan Sequence consists of a Palaeoproterozoic magmatic arc terrane dated at between 2.05 Ga and 1.8 Ga (Rainaud et al., 1999). On this basement the (as yet undated) Muva supracrustal succession of conglomerates, orthoquartzites and shales was deposited. This was then intruded by the 880 Ma Nchanga Granite, followed immediately by the Katangan Sequence (Armstrong et al., 1999). To the west , the Katangan Sequence is flanked by the c. 1.3-1.0 Ga Kibaran Belt, which separates it from the Neoarchaean rocks of the Kasai Craton (Delhal et al., 1975, 1976; Delhal 1977; Cahen et al., 1984; Tack et al., 1999).

Detrital zircons

Detrital zircons were separated from a sample of crossbedded Muva quartzite (MVQ1), which was collected south of Mufulira (Zambia) at 21°12'E, 12°36'S. 51 U-Pb analyses were carried out on 49 detrital zircons from this sample, using the SHRIMP at ANU. The results are plotted on a concordia diagram in Figure 1a, and the age distributions are shown on a histogram plot in Figure 1b. The detrital zircons form several distinct populations, which range in age from 3180 to 1941 Ma. The youngest detrital zircons form a cluster of ages peaking around 1.99 Ga, ranging from 1941±40 Ma (which is the maximum age for the Muva quartzite) to 2099±15 Ma. A second cluster of ages has a peak at about 2.19 Ga, and ranges from 2114 ±39 to 2262±17 Ma. A third group of ages ranges from 2371±17 to 2400±19 Ma. A fourth group of zircons has ages which range from 2463±25 Ma to 2708±18 Ma. This group has a bimodal distribution, with peaks at around 2.5 Ga and 2.7 Ga. There is a last group of zircons whose ages range from 3007±15 to 3031±6 Ma, with a peak at around 3.02 Ga. Finally, the oldest detrital zircon is dated at 3180±12 Ma.

Xenocrystic zircons

Numerous xenocrystic zircons were found in a lapilli tuff (S11) from the Mwashya Group in the Katangan Sequence, sampled at Shituru Mine (26°50'E, 11°01'S) near Likasi in the central part of the Lufilian Arc of folded Katangan rocks, in Katanga, D.R. Congo. The tuff itself is dated at c. 760 Ma, on the basis of 3 magmatic zircons (Armstrong et al., in prep.). The 44 dated xenocrystic zircons form several distinct populations ranging in age from 1068 to 3225 Ma. Some of these zircon populations have ages which overlap with those from the detrital zircon population in the Muva quartzite. However, some groups of zircons from the detrital suite are not represented in the xenocrystic zircon suite, and the xenocrystic zircons include a young population of Mesoproterozoic zircons which is completely absent from the

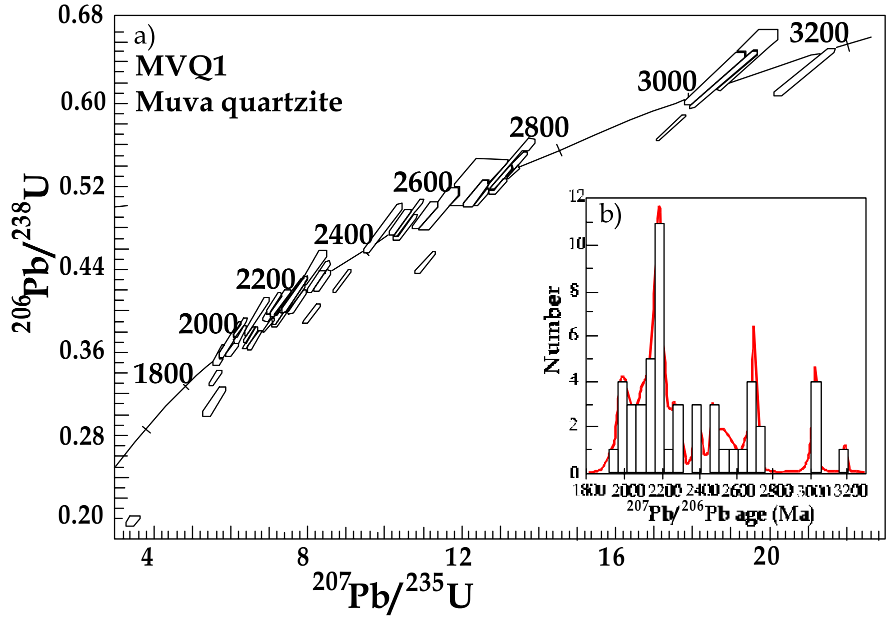

Figure 1*. a) $^{206}Pb/^{238}U$ vs $^{207}Pb/^{235}/U$ concordia plot of ages (Ma) of detrital zircons from the Muva quartzite, sample MVQ1. b) Histogram plot of $^{207}Pb/^{206}Pb$ ages of the detrital zircons.*

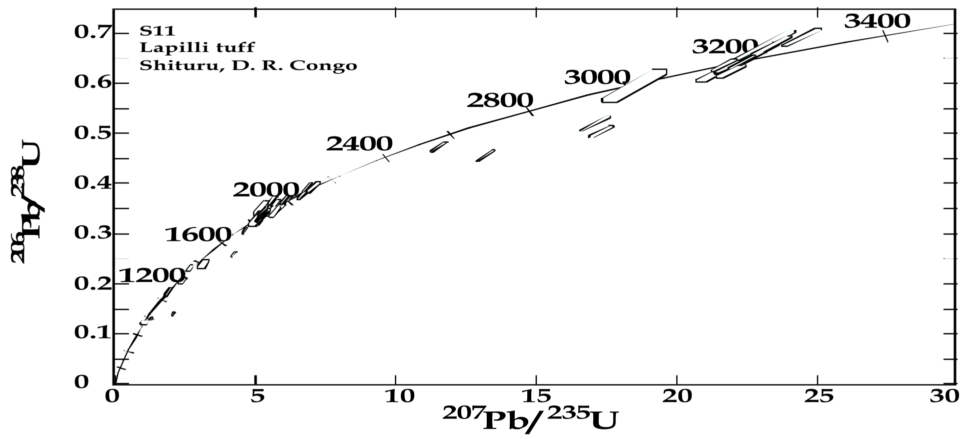

Figure 2 *$^{206}Pb/^{238}U$ vs $^{207}Pb/^{235}/U$ concordia plot of ages (Ma) of inherited xenocrystic zircons from lapilli tuff (sample S11), Mwashya Group, Katangan Sequence.*

detrital zircon population in the Muva quartzites. The youngest xenocrystic zircon population, comprising 5 zircons, or 11.4% of the total sample of dated xenocrystic zircons, is dated at between 1068±20 and 1384±48 Ma. A second group of 23 zircons (52.3%) has Palaeoproterozoic ages between 1791±21 and 2105±25 Ma, with a peak at c. 1860 Ma. There is a single zircon (2.3%) dated at 2624±9 Ma, and another solitary zircon dated at 3021±34 Ma. Finally, there is a large group of 14 zircons (32%) which are dated at between 3169±13 and 3225±11 Ma.

Provenance of zircons

The youngest xenocrystic zircons in the Katangan tuff (c. 1070 to 1385 Ma) span the age of the Kibaran granites (1375 to 1000 Ma, Tack et al., 1999), and indicates the presence of Kibaran magmatic rocks beneath the central part of the Lufilian Arc. The absence of Kibaran-aged zircons from the detrital population in the Muva quartzite (which is derived from a much wider area than that sampled by the tuff) is significant, and indicates that the Muva quartzites were most probably deposited before 1384±48 Ma. The large population of Palaeoproterozoic detrital and xenocrystic zircons, dated between 1791 and 2105 Ma, overlaps the time period (1.8 to 2.05) of the Ubendian magmatic arc terrane that constitutes the Bangweulu Block and the exposed basement in the Zambian Copperbelt (Rainaud et al., 1999). A younger group of c. 1860 Ma xenocrystic zircons from the tuff is not represented in the detrital zircon population from the Muva quartzite. The 2114 to 2262 Ma detrital zircons are from an unknown provenance, since there are no dated rocks of this age in the immediate vicinity, and this population is absent from the xenocrystic zircon suite. They may be derived from the Magondi Belt of Zimbabwe, which has been dated at between 2.16 and 2.12 Ga (Master, 1991; Schidlowski & Todt, 1998; Höhndorf & Vetter, 1999). The earliest Proterozoic suite of detrital zircons, dated at between 2371 and 2400 Ma, may be derived from the Luiza metasediments in the Kasai region of Congo, which have been dated at c. 2.4 Ga (Cahen et al., 1984), or from the c. 2.4 Ga granulites of the Kasai-Lomami complex (Delhal et al., 1986). The largely Neoarchaean suite of detrital zircons, dated between 2.46 to 2.71 Ga, appears to have been derived mainly from the Kasai Craton in Congo, NE Angola and NW Zambia, where granites and migmatites have been dated at 2.54 to 2.56 Ga (Key & Banda, 1999), and where 2.87 Ga leucogranites were overprinted at 2.7 to 2.6 Ga (Delhal, 1977). Neoarchaean rocks do not appear to be abundant in the crust beneath the Lufilian Arc, since only one xenocrystic zircon of this age (2624 Ma) was found in the Katangan tuff. The most enigmatic zircons from both the detrital and xenocrystic suites are the >3.0 Ga (Mesoarchaean) zircons which fall into two clusters, at c. 3.02 and 3.20 Ga. In the whole of Central Africa, there are no rocks that have been dated at 3.2 Ga, while only a few dates of c. 3 Ga are known, in widely separated regions such as Gabon and southern Zimbabwe (Cahen et al., 1984).

Cryptic Mesoarchaean terrane

There are no exposed rocks in the immediate vicinity of the Muva quartzites (or their proximal source regions) which are between 3.0 and 3.2 Ga in age. In eastern Zambia, Liyungu and Vinyu (1996) have obtained Pb model ages of 3047+/-130 Ma for zircons from the Chipata granite, and 2985+/-1.4 Ma for zircons from the Lutembwe granulite. The oldest dated rocks of the Archaean Kasai craton of Congo and NE Angola are c. 2.9 Ga (Delhal, 1977; Delhal et al., 1975). The greenstone belts and granites of Gabon, which constitute the western part of the Congo-Kasai craton, have been dated at 3.1-2.9 Ga (Caen-Vachette et al., 1988). The Zimbabwe Archaean craton consists mainly of 2.9 to 2.6 Ga granite-greenstone terranes, with only the southernmost Tokwe terrane containing older rocks dated at between 3.5 and 2.95 Ga (Kusky, 1998). The Archaean Tanzanian craton is dated at between 2.93 and 2.53 Ga (Pinna et al., 1999). In none of these regions have 3.2 Ga rocks been found. The detrital zircon population in the Muva quartzite has just one older Mesoarchaean zircon of 3.18 Ga age, and several zircons in the age range 3007 to 3031 Ma. By contrast, the Katangan tuff contains abundant older Mesoarchaean xenocrystic zircons dated between 3169 and 3225 Ma, and only one younger zircon dated at 3021 Ma.

The xenocrystic zircons originated from either the partially molten source region or the wallrocks on the path of ascent of the magmas that gave rise to the sampled Katangan tuffs. The lapilli tuffs at Shituru (which are interbedded with agglomerates) are the thickest and most proximal of all the tuffs in the Mwashya Group of the Katangan Sequence. The xenocrystic zircons in these tuffs therefore are a sample of the crust beneath the central part of the Lufilian Arc, which is buried under the tectonically thickened Katangan Sequence. The abundance of c. 3.2 Ga xenocrystic zircons in this tuff (32% of the total population) indicates that a substantial part of the crust beneath the central Lufilian Arc is a terrane of c. 3.2 Ga in age. The bulk of the rest of this crust is of Palaeoproterozoic (Ubendian) age, between 2.1 and 1.8 Ga. There is also evidence from these xenocrystic zircons for some Kibaran-aged crust (1.3 to 1.0 Ga) in this region. Because only one c. 3.2 detrital zircon was found in the Muva quartzite, it appears that the 3.2 Ga crust is probably poorly exposed at the surface (which is dominated by the c. 2 Ga Ubendian crust), and may be more abundant in mid- or deep crustal levels beneath the Lufilian Arc. The xenocrystic and detrital zircons from the Katangan tuffs and Muva quartzites provide the only direct evidence for the existence of this cryptic Mesoarchaean crust beneath the Katangan Sequence. The occurrence of diamonds in the kimberlite pipes of the Kundelungu Plateau to the north of the Lufilian Arc may be an indirect indication of the presence of old Archaean crust beneath the Katangan of Central Africa.

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NEW AGE CONSTRAINTS ON PROTEROZOIC OROGENIC EVENTS IN CENTRAL AND SOUTHERN AFRICA

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In Central and Southern Africa, Proterozoic crustal evolution is related to the Palaeoproterozoic Ubendian, Mesoproterozoic Kibaran-Irumide-Lurio and Neoproterozoic Katangan-Damaran orogenies. Recent single-zircon SHRIMP U-Pb dating studies have provided a new geochronological framework for Proterozoic orogenesis in this region. The basement rocks in the Central African Copperbelt comprise an Ubendian magmatic arc terrain of calc-alkaline granitoids and associated metavolcanics (Lufubu Schists), which have been dated at between 1991 and 1874 Ma. The 2049 Ma Mkushi gneisses of central Zambia are considered part of the magmatic arc. The Muva quartzites, overlying this basement, have detrital zircons ranging in age from 3.18 Ga to 1.941 Ga, the latter age being the maximum age for the Muva. The Nchanga Granite, dated at 877±11 Ma, gives a maximum age for the nonconformably overlying Katangan Sequence. The basal Katangan Roan Supergroup contains detrital zircons dated at ca. 880 Ma and 2.0-1.8 Ga. The newly recognised Ngamiland Belt (1234 to 1019 Ma) of NW Botswana and Namibia may form a link with Mesoproterozoic terrains of Namaqualand, South Africa, where Ubendian, Kibaran and Namaquan episodes have been delineated. Granite gneisses of the Gladkop and Little Namaqualand suites have emplacement ages of 2.02-1.82 Ga and 1.22-1.17 Ga respectively, with metamorphic overprinting at 1.06 Ga. The Namaquan episode, dated at 1.06-1.03 Ga, was a period of crustal thickening and magmatism, which was responsible for and coeval with the peak of meta- morphism. Low pressure granulite-facies metamorphism resulted from advective heating and crustal thickening by magmatic intrusions over a 30 Ma period.

CONTRIBUTIONS TO THE GEOLOGY AND MINERALIZATION OF THE CENTRAL AFRICAN COPPERBELT: I. NATURE AND GEOCHRONOLOGY OF THE PRE-KATANGAN BASEMENT

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SYNOPSIS

U-Pb SHRIMP zircon age data from the basement of the Katangan Sequence in the Central African Copperbelt show the existence of Neoproterozoic, Paleoproterozoic and Mesoarchaean terranes. The Nchanga red granite showed an age of emplacement of 887 ± 11 Ma. The calc-alkaline metavolcanic Lufubu schists from Zambia and the Democratic Republic of Congo have been dated respectively at 1968 ± 9 and 1873 ± 8 Ma. Fertile granitoids intercepted in drill cores located in the Zambian Copperbelt yield ages ranging from 1952 to 1994 Ma. Granitic gneiss from the Mkushi copper mine south of the Zambian Copperbelt has an age of 2049 ± 6 Ma. The Mulungushi bridge gneiss gives an age of 1976 ± 5 Ma. Zircons from the Mkushi aplites have xenocrystic cores (2035 ± 22 Ma) and rims dated at 1088 ± 159 Ma. Quartzite from the Muva Supergroup, which unconformably overlies the crystalline basement, exhibits a broad range of detrital zircon ages from 3180 Ma down to 1941 Ma. Furthermore, a population of xenocrystic zircons from a Katangan lapilli tuff has ages of c. 3200 Ma and provides, together with the data from the Muva quartzite, the first evidence of a cryptic Mesoarchaean basement beneath the Central African Copperbelt.

INTRODUCTION

The Central African Copperbelt, hosted by the Neoproterozoic metasediments of the Katangan Sequence is located in Zambia and the Katanga Province of the Democratic Republic of Congo (D.R.C.). The Copperbelt is one of the great metallogenic provinces of the world, being a leading producer of Cu and Co, as well as lesser amounts of Pb, Zn, Ge, Ga, U, Au and PGE (Master, 1998). It has long been recognised that the basement to the Katangan Sequence in the Copperbelt contains abundant copper mineralization, and many authors have regarded this as having an important bearing on the origin of the Copperbelt ores. This pre-Katangan basement consists of schists of the Lufubu Group, which are intruded by a variety of granitoids, both of which are unconformably overlain by metaquartzites and schists of the Muva Supergroup. This study provides new geochronological insight on this basement.

Although the Central African Copperbelt has a strike length of 500 km in the Lufilian Arc of Katanga (D.R.C) and Zambia, the pre-Katanga basement is mainly exposed in the Zambian Copperbelt and in immediately adjacent areas of Katanga. About half of this basement consists of granitoids, and the rest comprises mainly Lufubu schists with subordinate areas of Muva quartzite.

The Lufubu schists consist mainly of biotite or muscovite and quartz-bearing micaceous schists and quartzites, with minor accessory plagioclase, tourmaline, sphene, zircon, calcite and pyrite. Previously regarded as of metasedimentary origin (Mendelsohn, 1961), the Lufubu schists are calc-alkaline metavolcanics ranging from trachyandesite to rhyodacite and rhyolite (Rainaud et al., 1999).

The granitoids are commonly seen as intruding into the Lufubu schists. Their composition range from biotite granites to quartz monzonites, granodiorites and tonalites (Mendelsohn, 1961). Previous work on these granitoids yielded imprecise ages (Cahen et al, 1984; Ngoyi et al, 1991). The Muva Supergroup unconformably overlies the Lufubu schists and comprises mainly quartzites with minor conglomerates and argillaceous beds (Garlick, 1961).

GEOCHRONOLOGY

We present zircon U-Pb ages of the intermediate to felsic metavolcanic Lufubu schists from both the D.R. Congo and Zambia, several granitoids including the Mkushi gneiss, the Samba porphyry, a granite intersected in boreholes through the Chambishi Basin, the Mulungushi Bridge augen gneiss, the Mkushi aplite and the Nchanga Red granite as well as detrital zircons from the Muva Supergroup. Finally, we will present xenocrystic zircon data from a Katangan lapilli tuff located in D.R.C.

15 analyses have been carried out on 15 zircons from the Kinsenda Lufubu schists (D.R.C). The results are plotted on the concordia diagram in Figure 1. The age is well constrained at 1873 ± 8 Ma and is interpreted as the age of the volcanism in the area. Results of 15 analyses undertaken on one sample of Mufulira Lufubu schists (Zambia) are plotted on the concordia diagram in Figure 2. Three clusters of zircons are discernible. One zircon yields an age of 2174 ± 13 Ma whereas 3 zircons yielded an average mean $^{207}Pb/^{206}Pb$ of 2057 ± 9 Ma. These older zircons are interpreted as inherited. The last group of 10 zircons yielded a weighted mean $^{207}Pb/^{206}Pb$ of 1968 ± 9 Ma (Figure 3). This age is interpreted as the age of volcanic emplacement of the Mufulira Lufubu Schists. The volcanism of the Lufubu schists thus spanned a period of about 95 Ma.

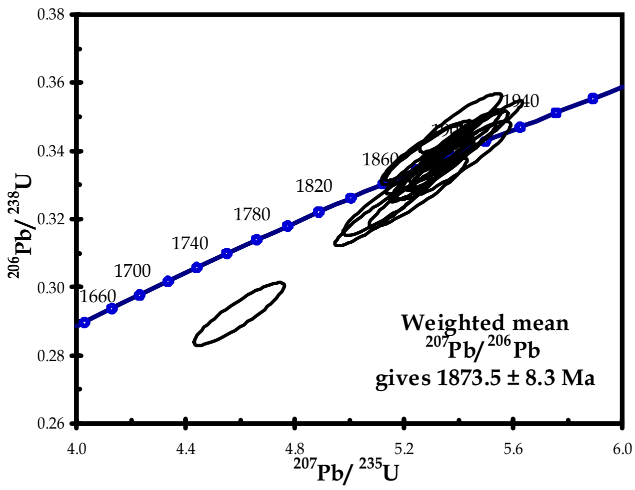

Figure 1: $^{206}Pb/^{238}U$ vs $^{207}Pb/^{235}U$ concordia plot of ages (Ma) of the Kinsenda Lufubu schists.

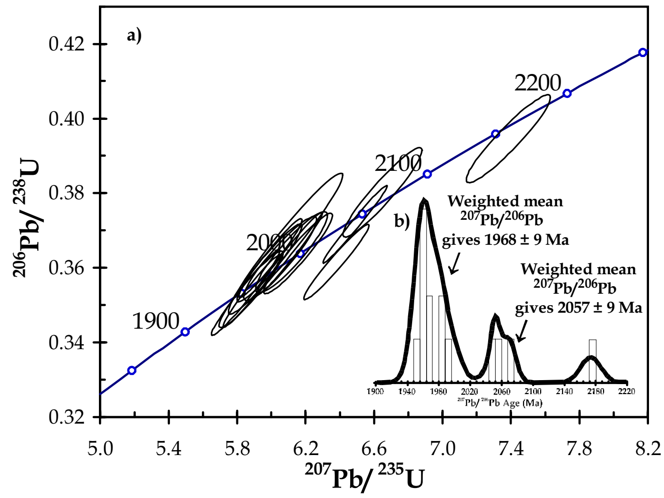

Figure 2: a) $^{206}Pb/^{238}U$ vs $^{207}Pb/^{235}U$ concordia plot of ages (Ma) of the Mufulira Lufubu schists. b) Histogram plot showing the relative distribution of $^{207}Pb/^{206}Pb$ ages of the zircons.

The Mkushi gneiss yielded an emplacement age of 2049 ± 6 Ma (Rainaud et al., 1999), which makes it the oldest dated rock unit in the Palaeoproterozoic basement of the Copperbelt. The Mufulira granite yielded an age of emplacement at 1991 ± 3 Ma. The Mulungushi Bridge megacrystic augen gneiss has an age of 1976 ± 5 Ma. The Samba porphyry is a mineralized granodiorite with copper ore reserves estimated at 50 million tons (Wakefield, 1978). Analyses yielded an age of emplacement of 1964 ± 12 Ma (Figure 3). For the granite underlying the Chambishi basin, 2 different samples from different drill holes (NN75 and BN53) were analysed. They yielded 2 similar ages of emplacement: 1983 ± 5 and 1980 ± 7 Ma respectively (Figures 4). A few zircons from the Mkushi aplites at Mtuga Mine were analysed. Three cores, interpreted as xenocrystic, gave ages of 2036 ± 22 Ma, while two rims were dated at 1088 ± 159 Ma. Recent investigations on the Nchanga red granite gave an age of emplacement of 887 ± 11 Ma (Armstrong et al., 1999).

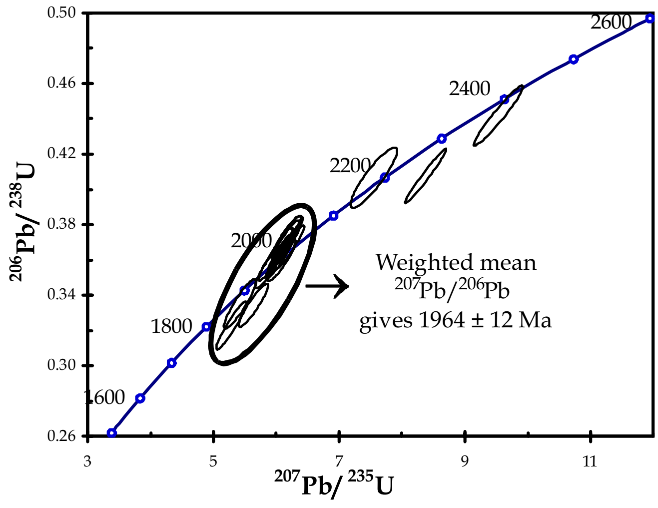

Figure 3: Concordia diagram of the Samba porphyry.

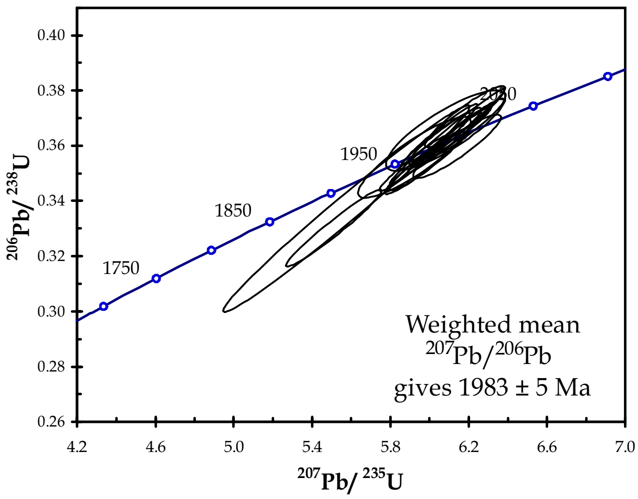

Figure 4: Concordia diagram of the granite beneath the Chambishi basin from borehole NN75.

50 detrital zircons from a Muva quartzite south of Mufulira, Zambia were analysed. The results are plotted on the concordia diagram in Figure 5. An Archaean component is observed with ages clustering at 2550 to 2700 Ma and also at around 3000 to 3180 Ma. Palaeoproterozoic zircons range down to 1941 Ma, the youngest zircon in the population and an indication, therefore, of the maximum age of the deposition for the Muva Supergroup.

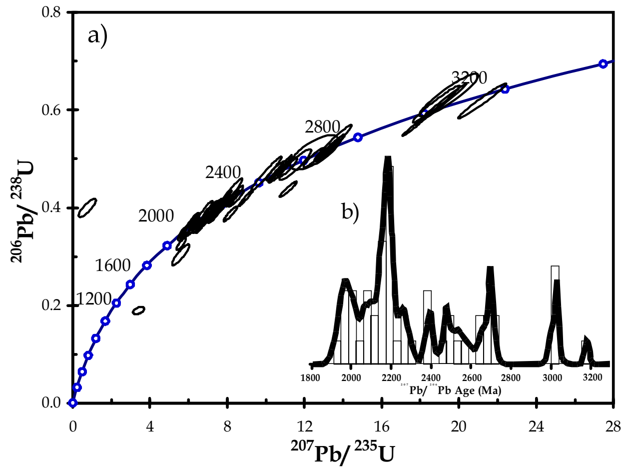

Figure 5: a) $^{206}Pb/^{238}U$ vs $^{207}Pb/^{235}U$ concordia plot of ages (Ma) of the Muva quartzite. b) Histogram plot showing the relative distribution of $^{207}Pb/^{206}Pb$ ages of the zircons.

A Katangan lapilli tuff from the Mwashya Group, Likasi, D. R. C., yielded a population of zircons. Out 48 analyses undertaken on zircons from this sample, 43 were concordant and older than the maximum age of the deposition of the Katangan Sequence. These zircons were therefore interpreted as xenocrystic. They form several age populations but for the purpose of this paper, the attention will be drawn to the oldest one. 14 zircons yielded ages ranging from 3169 ± 13 Ma to 3225 ± 11 Ma.

These ages are older than that of any rock so far described from Central Africa (Rainaud et al., 2000).

CONCLUSIONS

The basement to the Katangan Sequence in the Central African Copperbelt comprises a Palaeoproterozoic magmatic arc. Tonalite-granodiorite gneisses (Mkushi) together with more evolved granitoids (Mufulira, Mulungushi, Samba and Chambishi) represent the plutonic phases of a major intermediate to acid volcanic province (Lufubu schists) emplaced in the range 2050 to 1865 million years ago. Unconformably overlying this part of the basement is the Muva Supergroup, younger than 1941 Ma, which contains detrital zircons of Palaeoproterozoic to Mesoarchaean age. There are no exposed rocks between 3200 and 3000 Ma in the vicinity of the Muva quartzite. This age range is found as well in xenocrystic zircons located in a Katagan tuff from Likasi. The abundance of c. 3200 Ma xenocrystic zircons in this tuff indicates that a part of the crust beneath the central Lufilian Arc is a Mesoarchaean terrane.

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CONTRIBUTIONS TO THE GEOLOGY AND MINERALIZATION OF THE CENTRAL AFRICAN COPPERBELT: II. NEOPROTEROZOIC DEPOSITION OF THE KATANGA SUPERGROUP WITH IMPLICATIONS FOR REGIONAL AND GLOBAL CORRELATIONS

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SYNOPSIS
We present some new data constraining the depositional age of key units within the Neoproterozoic Katanga Supergroup, which hosts the major stratiform Cu-Co deposits of the Central African Copperbelt. The older age limit on basal Roan Group sedimentation is 880 Ma, which is the age of the youngest detrital zircons. The ages of volcanics in the Mwashya Group (760 ± 5 Ma), and a volcanic unit assigned to the Lower Kundelungu (735 ± 5 Ma) bracket the age of the Grand Conglomerat, and allows its correlation with other Neoproterozoic glacial diamictites (e.g., Chuos, Sturtian). Finally, detrital muscovites from Plateau Group siltstones give a maximum age of sedimentation of 565 ± 5 Ma, strongly supporting the idea that the Plateau Group was deposited in a foreland basin of the Lufilian Orogen. Detrital zircon ages indicate a mainly Palaeoproterozoic provenance area for the Katanga basin, with only minor contributions from Archaean and Mesoproterozoic (Kibaran) source regions.

INTRODUCTION
The Neoproterozoic Katanga Supergroup is the host of the major stratiform sediment-hosted Cu-Co deposits, as well as numerous other deposits of Cu, Pb, Zn, U, Au, Fe etc., which constitute the Central African Copperbelt in Zambia and the Democratic Republic of Congo. In spite of its great economic significance there have been, up to now, few age data bearing on the deposition of the Katangan Sequence.

REGIONAL GEOLOGICAL SETTING
In the Central African Copperbelt, the oldest pre-Katangan basement consists of a Palaeoproterozoic magmatic arc sequence, comprising the Lufubu Schists and intrusive granitoids, dated at between 1994 and 1873 Ma. This is overlain unconformably by quartzitic and metapelitic metasediments of the Muva Group (<1941 Ma). The Nchanga Granite is the youngest intrusion in the pre-Katangan basement, and it is nonconformably overlain by the Katangan Sequence, which consists of metasediments traditionally divided into the Roan, Lower and Upper Kundelungu Supergroups. More recently, Wendorff (2001) has proposed a new lithostratigraphic scheme, in which the Katanga Supergroup is subdivided into the Roan, Mwashya and Guba Groups, with two additional lithotectonic units, the Fungurume and Plateau Groups, which were deposited syntectonically in a foreland basin during deformation of the earlier Katangan groups during the Pan-African Lufilian Orogeny.

NCHANGA GRANITE
The Nchanga Granite is an unfoliated coarse-grained peraluminous biotitic alkali granite with A-type geochemical characteristics (Tembo et al., 2000). SHRIMP U-Pb dating of zircons from the

Nchanga Granite has yielded a concordant age of 877 ± 11 Ma, regarded as the age of the intrusion (Armstrong et al., 1999).

KATANGA SUPERGROUP- LOWER ROAN GROUP SEDIMENTS

Conglomeratic and arkosic sediments of the siliciclastic unit in the lower Roan Group at Nchanga Mine nonconformably overlie the Nchanga Granite. Previous studies have indicated that there are pebbles and zircons from the Nchanga Granite in basal Roan conglomerates, suggesting that the lower Roan sediments are derived by erosion of a basement that included the Nchanga Granite. We sampled a suite of detrital zircons from a crossbedded Roan arkose about 10 metres above the contact with the Nchanga Granite in borehole P322 drilled underground at Nchanga Mine. U-Pb SHRIMP dating of these detrital zircons reveals two distinct age populations (Figure 1), one at around 2.0 to 1.8 Ga (corresponding to the age of the Palaeoproterozoic basement), and the other at 880 Ma (coresponding to the age of the Nchanga Granite). This unequivocally proves that the Nchanga Granite provided detritus to the Lower Roan, and sets a firm older limit of c. 880 Ma for the age of the Katanga Supergroup.

Detrital zircons from several other samples of lower Roan Group sediments from Mine de l'Etoile, Musoshi, Konkola, and the Chambishi Basin were U-Pb dated with the SHRIMP. Most of the samples have zircons almost exclusively of Palaeoproterozoic age with a few older and younger ages. Unless otherwise indicated, all ages quoted are $^{207}Pb/^{206}Pb$ ages on zircons that are < ± 10% discordant on a $^{206}Pb/^{238}U$ vs $^{207}Pb/^{235}U$ concordia diagram. The sample from Etoile had two zircons of late Archaean age (2831 ± 16 and 2802 ± 36 Ma), and one zircon dated at 1858 ± 24 Ma. Two samples from Musoshi had detrital zircons in the age ranges 1883 ± 21 to 2066 ± 20 Ma (MUS3, 10 analyses) and 1789 ± 35 to 2081 ± 28 Ma (SPOTMU, 46 analyses) respectively. A sample from Konkola (KNS7, 14 analyses) yielded a similar detrital zircon age range to the Musoshi samples, from 1836 ± 26 to 1996 ± 15 Ma. The sample from the Chambishi Basin (RCB2/4, 17 analyses) yielded the following ages of detrital zircons: 908 ± 40 Ma; 891 ± 119 Ma [115% concordant]; 1152 ± 65 Ma; 1301 ± 46 Ma; 1813 ± 28 to 2062 ± 38 Ma. In addition, 42 zircons from the same sample were analysed only for $^{206}Pb/^{238}U$, and yielded less reliable $^{206}Pb/^{238}U$ ages as follows: 1282 ± 31 Ma; 1711 ± 36 to 2200 ± 48 Ma; 2431 ± 37 Ma; 2840 ± 69 to 2857 ± 60 Ma. These data indicate that the source region for the Lower Roan sediments consisted mainly of Palaeoproterozoic rocks dated between 1790 and 2200 Ma (derived from the Palaeoproterozoic magmatic arc terrain), with minor contributions from older Neoarchaean rocks (c. 2860 to 2800 Ma) (possibly derived from the Kasai Craton) and some younger Mesoproterozoic to early Neoproterozoic rocks (c. 1300 to 900 Ma), possibly derived from the Kibaran Belt.

MWASHYA GROUP

The Mwashya Group, lying above the Roan Group, consists mainly of carbonates and black shales, but contains a thin pyroclastic unit with associated stratiform banded magnetite/haematite iron formations, which form a regional stratigraphic marker. The pyroclastics, mainly mafic lapilli tuffs and agglomerates, are best developed at Shituru Mine near Likasi (D. R. Congo). An attempt was made to date zircons from these pyroclastics (sample S11), but they turned out to be entirely xenocrystic, with ages ranging from 3225 to 1068 Ma (Rainaud et al., 2000). Another sample (S27-S32) of agglomerate from borehole S1 at Shituru Mine yielded three xenocrystic zircon grains with U-Pb SHRIMP ages of 1870 ± 15, 1047 ± 25 and 983 ± 50 Ma, reflecting inheritance from Palaeoproterozoic and Kibaran rocks. In western Zambia, in the Mwinilunga area, Key and Banda (2000) have mapped a several hundred metres thick volcanic unit within the Mwashya Group, the Lwavu Formation, which consists of basalts and basaltic andesites. These volcanics have been dated at 760 ± 5 Ma, utilising SHRIMP U-Pb dating on zircons (Armstrong, 2000; Liyungu et al., 2001; Key et al., 2001). This is the first accurate date for any Katangan lithological unit.

KUNDELUNGU/ GUBA GROUP

To the southeast of the Mwinilunga area, strongly deformed and poorly differentiated Katangan rocks of the West Lunga Formation, comprising shales, dolomites, siltstones, diamictites, banded iron formations and porphyritic volcanics, have been provisionally correlated with the Kundelungu Supergroup (Liyungu et al., 2001). One of the porphyritic lavas in this area has been dated with the SHRIMP (U/Pb on single zircons) at 735 ± 5 Ma (Armstrong, 2000; Liyungu et al., 2001). We also dated a suite of detrital zircons from the Grand Conglomerat at Kipushi Mine (sample K30-K41, borehole KHI 115034HZ-5, 150-207 m). These detrital zircons have ages ranging from Palaeoproterozoic to Neoproterozoic, as follows: 1945 ± 15 – 1846 ± 22 Ma (6 zircons); and 1025 ± 86 – 822 ± 42 Ma (4 zircons). One zircon gave an age of 729 ± 50 Ma, but it was only 88% concordant.

PLATEAU GROUP

Detrital muscovites from red siltstones of the Plateau Group collected in the Kundelungu Plateau National Park, Katanga, D.R. Congo, were dated using the laser $^{40}Ar/^{39}Ar$ technique. The results of laser probe spot fusion of seven individual detrital muscovite grains show a range of $^{40}Ar/^{39}Ar$ ages between 635 and 565 Ma, with one age of 1472.4 ± 5 Ma (Figure 2). The youngest detrital muscovite age of 565 ± 5 Ma is regarded as the maximum age for the sediments of the Plateau Group, which are thus constrained to be terminal Neoproterozoic and/or Palaeozoic in age. 50 detrital zircons from the same sample (KPM3) were dated using U-Pb (SHRIMP)- of these, 47 ages were <±10% discordant. These ages range from 1977 ± 11 – 1780 ± 37 Ma (45 zircons) and 1219 ± 113 – 1176 ± 62 Ma (2 zircons). One zircon had a young age of 463 ± 118 Ma, but it was 144% concordant, and plotted above the concordia curve.

DISCUSSION

The deposition of the Katanga Supergroup started at some time after 880 Ma. The ages of volcanic units in the Mwashya and Lower Kundelungu (Guba) Groups bracket the age of the Grand Conglomerat between 760 ± 5 and 735 ± 5 Ma. This allows the correlation of the Grand Conglomerat with other Neoproterozoic glacial diamictite units such as the Chuos diamictite in the Damara Orogen (Namibia) and the Sturtian diamictites of the Adelaidean Supergroup, South Australia. The age of the Petit Conglomerat is not yet well constrained. The Plateau Group of the Katanga Supergroup now has a maximum age of 575 ± 5 Ma based on laser ^{40}Ar-^{39}Ar dating of detrital muscovites. The Plateau Group was thus deposited either in the terminal Neoproterozoic, or in the early Palaeozoic, and this timing strongly supports models which regard the Plateau Group as being deposited in a foreland basin to the Pan-African Lufilian orogeny, rather than the earlier models which regarded it as having been deposited in an aulacogen. Detrital zircon ages indicate a mainly Palaeoproterozoic provenance area for the Katanga basin, with only minor contributions from Archaean and Mesoproterozoic (Kibaran) source regions.

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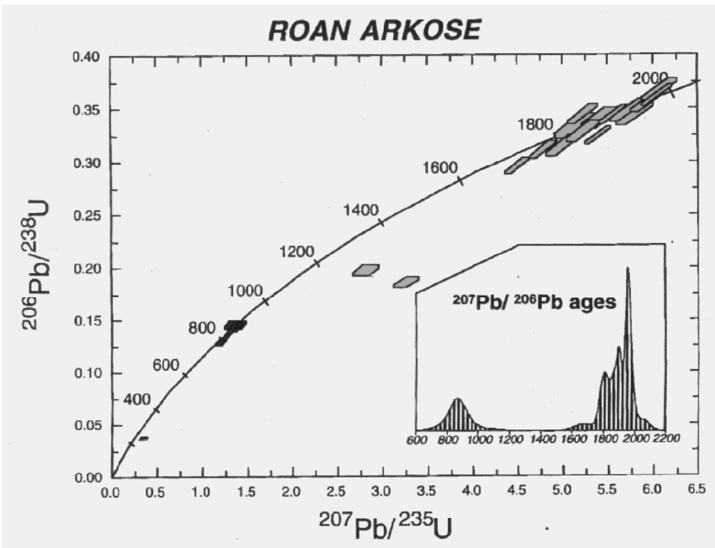

Figure 1: U-Pb concordia diagram showing the ages of detrital zircons from lower Roan Group arkose, 10 m above the contact with the Nchanga granite, Borehole P322, Nchanga Mine, Zambia.

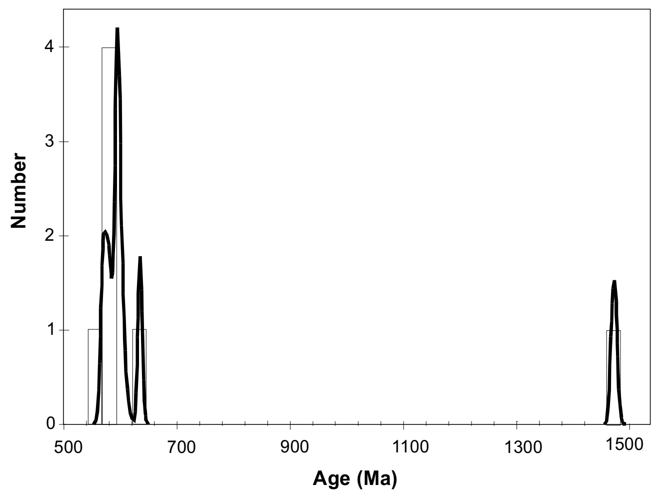

Figure 2: Histogram showing $^{40}Ar/^{39}Ar$ ages on individual detrital muscovite grains from a red siltstone of the Plateau Group, Kundelungu Plateau National Park, D. R. Congo

CONTRIBUTIONS TO THE GEOLOGY AND MINERALIZATION OF THE CENTRAL AFRICAN COPPERBELT: IV. MONAZITE U-Pb DATING AND ^{40}Ar-^{39}Ar THERMOCHRONOLOGY OF METAMORPHIC EVENTS DURING THE LUFILIAN OROGENY.

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SYNOPSIS

We present new SHRIMP U-Pb age data on metamorphic monazite, as well as step-heating $^{40}Ar/^{39}Ar$ plateau ages on metamorphic biotites and K-feldspar, from Katangan metasedimentary rocks from the Central African Copperbelt, which were deformed and metamorphosed during the Pan-African Lufilian Orogeny. Three samples of metamorphic monazites from the Chambishi structural basin give ages of 592 ± 22 Ma, 531 ± 12 Ma and 512 ± 17 Ma, which correspond respectively to the ages of eclogite facies metamorphism, talc-kyanite whiteschist metamorphism, and of a regional metamorphic/mineralization pulse elsewhere within the Lufilian orogen. A biotite from Luanshya gives a $^{40}Ar/^{39}Ar$ plateau age of 585.8 ± 0.8 Ma, while several samples from the Chambishi basin give $^{40}Ar/^{39}Ar$ biotite ages in the range of 493 to 485 Ma, and are a manifestation of regional uplift and cooling that affected the whole Katangan basin. The youngest age obtained is a $^{40}Ar/^{39}Ar$ K-feldspar age of 448.5 ± 0.7 Ma from Musoshi, coinciding with a period of late syenite intrusion.

INTRODUCTION

The Katanga Supergroup is the host of the major stratiform sediment-hosted Cu-Co deposits, as well as numerous other deposits of Cu, Pb, Zn, U, Au, Fe etc., which constitute the Central African Copperbelt in Zambia and the Democratic Republic of Congo. The Katanga Supergroup of Central Africa is a Neoproterozoic metasedimentary sequence which consists of the Roan and Mwashya Groups, the Guba Group (formerly Lower and Upper Kundelungu Groups, Wendorff (2001)), and the Fungurume and Plateau Groups. The lowermost Roan Group was deposited after c. 880 Ma, the Mwashya group was deposited around 765 Ma; the lower part of the Guba Group was deposited between 765 and 735 Ma and the upper part before c. 602 Ma, and the Fungurume and Plateau Groups were deposited syntectonically in a foreland basin during the Lufilian orogeny, after c. 570 Ma. The Katanga Supergroup was deformed and metamorphosed during the Pan-African Zambezi and Lufilian orogenies (Porada & Berhorst, 2000), at between c. 600 to 480 Ma. A large number of older U-Pb, Rb-Sr and K-Ar age data from the Lufilian arc and Zambezi belt, spanning the time period 500 ± 100 Ma are summarised by Cahen et al. (1984).

MONAZITE SHRIMP U-Pb DATING

Metamorphic monazite grains for U-Pb SHRIMP dating were extracted from samples collected from boreholes RCB1 and RCB2 which are from the Chambishi structural basin in the Zambian Copperbelt. Sample RCB2/72 is from an altered tuff (biotite retrograded to chlorite, quartz, carbonate) interbedded with iron formation within the Mwashya Group, at a depth of 497 m in borehole RCB2. Euhedral monazite intergrown with biotite or chlorite from this sample give a SHRIMP U-Pb age of 592 ± 22 Ma (Figure 1). Sample RCB1/36 is a quartz-chlorite schist from a depth of 1283 m in borehole RCB1. Monazites from this sample give a SHRIMP U-Pb age of 531 ± 12 Ma (Figure 2). Sample RCB2/112 is a marly dolomitic argillite, from a depth of 528 m in borehole RCB2. Monazites from this sample give a SHRIMP U-Pb age of 512 ± 17 Ma (Figure 3).

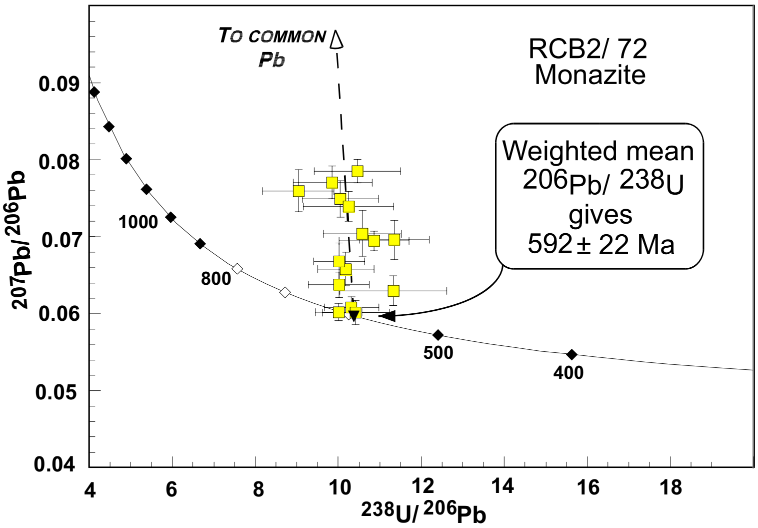

Figure 1: SHRIMP U-Pb age data on metamorphic monazite from RCB2/72 (Chambishi Basin, Zambian Copperbelt)

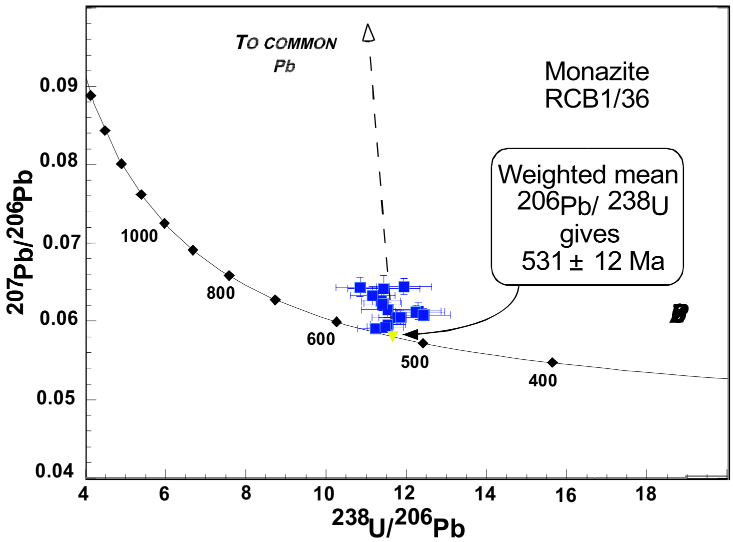

Figure 2: SHRIMP U-Pb age data on metamorphic monazite from RCB1/36 (Chambishi Basin, Zambian Copperbelt)

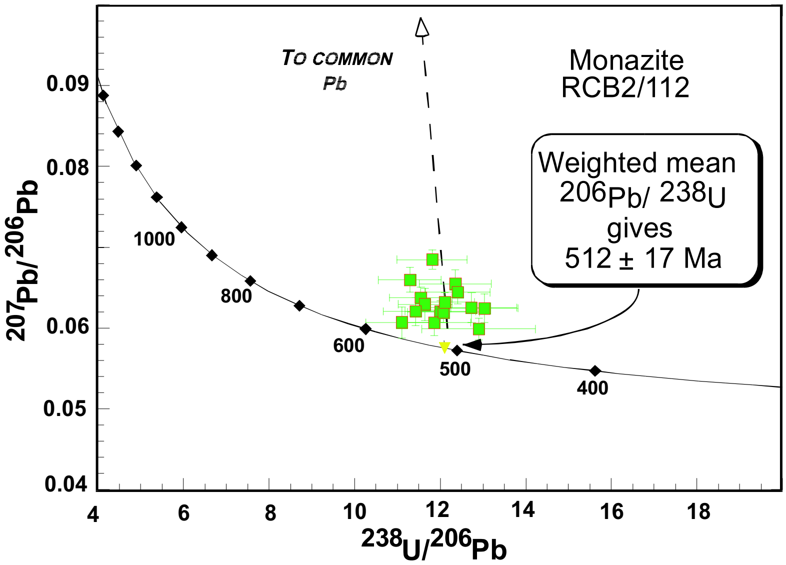

Figure 3: SHRIMP U-Pb age data on metamorphic monazite from RCB2/112 (Chambishi Basin, Zambian Copperbelt)

^{40}Ar-^{39}Ar THERMOCHRONOLOGY

Metamorphic biotites were extracted from a number of samples ranging stratigraphically from the Lower and Upper Roan and Mwashya groups to the Grand Conglomerat at the base of the Guba (Kundelungu) Group, and were dated using the step-heating ^{40}Ar-^{39}Ar dating technique. In addition, K-feldspar from one sample was dated using the same technique. The results are given in Table 1. Samples RCB2/112, RCB2/4, NN75/9 and MJZC9/25 are from boreholes drilled in the Chambishi Basin (Zambia); sample BH89/3 is from Luanshya (Zambia), and MUS1 is from Musoshi Mine (D.R. Congo).

Table 1: ^{40}Ar-^{39}Ar plateau ages of biotites and K-feldspar in metamorphic rocks from the Katanga Supergroup, Central African Copperbelt

Sample	mineral dated	^{40}Ar-^{39}Ar plateau age	Rock type	Stratigraphic position
BH89/3	biotite	585.8 ± 0.8 Ma	biotite-trem sch.	Lower Roan Gp
RCB2/112	biotite	492.6 ± 0.5 Ma	dolomitic marl	Mwashya Gp
NN75/9	biotite	487.3 ± 0.4 Ma	Rippled dolomite	Upper Roan Gp
RCB2/4	biotite	486.7 ± 0.6 Ma	Conglomerate	Lower Roan Gp
MJZC9/25	biotite	485.4 ± 0.9 Ma	Lam.grey shale	Grand Conglomerat Fm
MUS1	K-feldspar	448.5 ± 0.7 Ma	Arkose	Lower Roan Gp

DISCUSSION

In sample RCB2/72 the monazite U-Pb age of 592 ± 22 Ma is the oldest metamorphic age that we have found. This age is indistinguishable from the 595 ± 10 Ma Sm-Nd isochron age of eclogite facies metamorphism recorded from MORB-like metagabbroic eclogites from the Lufilian Arc of central Zambia (John et al., 2002). It is also similar to the 585.8 ± 0.8 Ma ^{40}Ar-^{39}Ar age of biotite from a biotite-tremolite schist from Luanshya (sample BH89/3). A similar Rb-Sr model age of 582 ± 40 Ma was recorded from the Kafue rhyolites in the Zambezi Belt (Cahen et al., 1984). Interestingly, no K-Ar or Rb-Sr ages of c. 600-570 Ma have been found in the Domes Area, where older biotite K-Ar ages in the range of 708 ± 7 to 628 ± 7 Ma have been recorded in the Lolwa area, northwestern Kabompo Dome, and one Rb-Sr muscovite age of 744 ± 8 Ma was recorded from the Malundwe area, Mwombezhi Dome (Cosi et al., 1992).

Monazites from sample RCB1/36 have a U-Pb age of 531 ± 12 Ma. This age is indistinguishable from monazite U-Pb ages of c. 530 ± 2 Ma recorded from four talc-kyanite whiteschist localities distributed throughout the whole Lufilian Arc and Zambezi Belt (John et al., 2002). A similar biotite K-Ar age of 525 ± 5 Ma is recorded in a biotite schist from the Mutanda Bridge between the Solwezi and Mwombezhi Domes (Cosi et al., 1992).

Two distinct periods of mineralized vein emplacement at Kansanshi Mine have been dated at 512 and 502 Ma, using Re-Os dating of molybdenite, and SHRIMP U-Pb dating of monazite (Torrealday et al., 2000). These discrete episodes of mineralization have been related to post-tectonic pulses of metamorphic fluids, which appear to be recorded basinwide in the Katangan. Thus, the 512 Ma age has also been reported for late uraninite and rutile veining at Musoshi Mine (Richards et al., 1988a,b), and for uraninite mineralization at Nkana Mine (Darnley et al., 1961). In the Mwombezhi Dome, a muscovite Rb-Sr age of 512 ± 6 Ma and biotite K-Ar ages of 510 ± 6 and 518 ± 6 Ma have been obtained from the Chantete area in the NE extremity, while a biotite K-Ar age of 507 ± 6 Ma has been obtained from the centrally located Malundwe area (Cosi et al., 1992). A sample from the Kafue rhyolites in the Zambezi belt has a Rb-Sr model age age of 512 ± 35 Ma (Cahen et al., 1984). Hence the age of 512 ± 17 Ma for monazite from the Chambishi Basin (RCB2/112) is a further manifestation of the regional basinwide metamorphic event at c. 512 Ma.

The younger biotite ^{40}Ar-^{39}Ar ages of 493 to 485 Ma reflect closure of the K-Ar system in biotite upon cooling to below 345-285°C (Harrison et al., 1985), and are a manifestation of regional uplift and cooling that affected the whole Katangan basin, since similar ages are widely recorded in the Domes Area of NW Zambia (Cosi et al., 1992), as well as in other parts of the Lufilian Arc (Cahen & Snelling, 1971). Our youngest ^{40}Ar-^{39}Ar age of 449 ± 1 Ma on K-feldspar from Musoshi Mine (reflecting cooling below c. 300-150° C) is similar to a muscovite Rb-Sr age of 450 ± 9 Ma age from Malundwe in the Mwombezhi Dome (Cosi et al., 1992). This young metamorphic event corresponds to the age (458-427 Ma) of the late nepheline-syenite Mukumbi intrusion north of the Mwombezhi Dome (Cosi et al., 1992).

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CONTRIBUTIONS TO THE GEOLOGY AND MINERALIZATION OF THE CENTRAL AFRICAN COPPERBELT: V. SPECULATIONS REGARDING THE 'SNOWBALL EARTH' AND REDOX CONTROLS ON STRATABOUND Cu-Co AND Pb-Zn MINERALIZATION

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SYNOPSIS

The major sediment-hosted Fe and Mn deposits of the world have formed by oxidative precipitation from ocean waters that are stratified in terms of redox state. There is mounting evidence that both Palaeoproterozoic Superior-type banded iron-formations and Neoproterozoic Rapitan-type iron ores formed in environments where fluctuations in redox states were influenced by global ice ages. Recent constraints on the age of the Katangan sequence in the Central African Copperbelt links much of its depositional history to the Cryogenian Period (850 to 650 Ma), during which time the Neoproterozoic 'Snowball Earth' occurred. This raises the question as to whether certain styles of stratiform sediment hosted copper (SSC) mineralization might also be genetically linked to the near-surface redox fluctuations that are associated with periods of global glaciation. Stratiform Cu-Co mineralization in the Copperbelt is early-to-late diagenetic in its timing and is suggested to be a product of the mixing of two fluids, one a pregnant oxidized solution and the other a reduced barren one. A source of reduced fluid might be compaction and diagenesis of sediments deposited during the global anoxia that accompanied the Sturtian/Chuos/Kaigas ice age at around 750 Ma. Fluids derived from such reduced sediments may also have been responsible for the formation of epigenetic Pb-Zn deposits hosted by cap carbonates. Our initial fluid inclusion studies indicate more than a single fluid population, although the relationship between fluids and the paragenetic sequence remains to be determined. Such a link needs to be tested by accurate age determinations of the stratabound mineralization events.

INTRODUCTION

The major sediment-hosted Fe and Mn deposits of the world have formed by oxidative precipitation from sea water that was stratified with respect to its redox state. Neoproterozoic Rapitan-type iron-formations formed in environments where fluctuations in near-surface redox states were influenced by two or more near-global ice ages, popularly referred to as the 'Snowball Earth' events (Hofmann & Schrag, 2000). There is mounting evidence that Palaeoproterozoic Superior-type banded iron-formations, as well as related bedded Mn ores, might also be related to a period of extensive low-latitude glaciation (Kirschvink et al., 2000). It is also intriguing to note that the Duitschland Formation of the Palaeoproterozoic Transvaal Supergroup is characterized by minor stratiform Cu deposits (Martini, 1979) hosted in limestones associated with diamictite units that are correlatable with the same low-latitude glaciogenic Makganyene diamictite with which the huge Fe and Mn ores of Griqualand West are linked (Bekker et al., 2001). Given that the solubilities of Cu, Co, Pb and Zn complexes in aqueous solution are redox sensitive, the question of environmental/climatic controls on the oxidative state of the near surface are perhaps also likely to be relevant to ore genetic considerations for the stratiform ores of the Central African Copperbelt. This is particularly so given the new constraints on the age of the Katangan sequence, a significant component of which was deposited during the Cryogenian Period (850 to 650 Ma).

RELEVANT GEOCHRONOLOGICAL CONSTRAINTS

We have recently provided U-Pb zircon geochronological constraints indicating that the Roan Group was deposited between 880 Ma (the age of the Nchanga granite and detrital zircons in the lower Roan sediments) and 760 Ma (a volcanic unit just below the Grand Conglomerat at the base of the Guba or Lower Kundelungu Supergroup; Key et al., 2001). A maximum age of the Upper Kundelungu (Plateau Group) sediments is provided by Ar-Ar ages of detrital muscovite of 565 Ma. The Katangan sequence was, therefore, deposited episodically over an extended period (>300 million years) of geological time. The two glacial diamictite units in the Katangan sequence, the Grand Conglomerat (GC) and Petit Conglomerat (PC) at the respective bases of the Lower and Upper Kundelungu Supergroups (now included in the Guba Group, Wendorff, 2001), are bracketed between 760 Ma and 580 Ma and are, therefore, possible correlatives of the Sturtian/Chuos/Kaigas (at circa 750 Ma) and the Marinoan/ Varangian/Numees (at circa 600 Ma) glaciogenic deposits that define the Snowball Earth freeze-over. The two glaciogenic horizons are characterized by cap carbonate units immediately overlying them. Magnetite- and haematite-rich BIF units (with minor Mn) below the GC in the Mwashya are correlated with similar iron formations in the Rapitan, Urucum, Damara and other sequences worldwide, which are a reflection of globally stratified oceans during the Cryogenian period. Evidence that the Mwashya sediments were deposited during the global ice ages comes from preliminary carbon isotope data, which show a negative excursion in del ^{13}C in the Mwashya, going to a minimum of –5 permil PDB in the Grand Conglomerat, and recovering to more positive values in the Kakontwe cap carbonates. The C isotope data permit a chemostratigraphic correlation between the Mwashya and Guba Groups, and other Neoproterozoic successions deposited during the Sturtian/Chuos glaciation.

There are few if any accurate age data constraining the timing of stratiform Cu-Co mineralization in the Copperbelt. A K-Ar age of 870±42 Ma (Cahen et al., 1984) for a microcline vein cutting stratiform ore is widely quoted, as is the range between 790 Ma and 750 Ma provided by Pb-Pb model ages for Pb-Zn mineralization from several deposits in the region (Kampunzu et al., 1999). However, Kamona et al. (1999) rejected the 3-stage “shale-curve” Pb-evolution model used by Kampunzu et al. (1999), and got ages of 680 Ma for Kabwe mineralization, and 456±18 Ma for Kipushi mineralization. Richards et al. (1988) provided a Pb-Pb model age of 645±15 Ma for Cu-Fe sulphides from the Musoshi Mine, a date interpreted as reflecting either primary ore deposition or Pb re-homogenization. Walraven and Chabu (1991) obtained a Pb model age of 823 Ma for Kinsenda copper sulphide mineralization. Given the long-lived depositional history of the Katangan sequences, it is clear that the concept of diagenetic mineralization is likely to be grossly diachronous and could itself have extended over an extended period of geological time. Diagenesis and related fluid flow in the lower Roan sediments were probably separated by more than 100 million years of time from those in the upper Mwashya and lower Kundelungu sequences.

NATURE OF STRATABOUND Cu-Co MINERALIZATION

Mineralization consists of disseminated copper and cobalt sulphide minerals (chalcocite, bornite, chalcopyrite, carrolite) occurring as dispersed grains, fracture fillings, near massive lenses and replacements of diagenetic pyrite, Fe-Ti detrital minerals and micaceous silicates. The sedimentary host rocks mainly form part of the lower Roan Supergroup and comprise a wide range of lithotypes, including basal continental clastics and aeolianites, shales and siltstones, evaporitic carbonates, dolomitic shales and stromatolitic bioherms. Much of the mineralization is linked to the ‘Ore Shale’, that was formed in a restricted marine or lacustrine environment, although many other sediment types are also mineralized. In at least one situation at Shituru Mine, stratiform mineralization is hosted by reduced volcaniclastic rocks in the Mwashya Group (Lefebvre, 1974). Unrug (1988) has emphasized the fact that stratiform Cu-Co mineralization is distributed throughout the Roan Supergroup but does not occur above the GC, into the Kundelungu sequences. Different scales of mineral zonation are evident in the district and, in general, there is metal segregation into Cu, Cu-Co and Pb-Zn rich zones.

NATURE OF Pb-Zn MINERALIZATION

Pb-Zn mineralization in the Katangan is epigenetic, and occurs in transgressive orebodies hosted in two different stratigraphic units. At Kabwe, Zambia, Pb-Zn-(V-Ga-Ge-Cd-Ag) mineralization in pipe-like bodies is hosted by carbonate rocks correlated with the Upper Roan Group. Highly saline (c. 30 wt.% eNaCl) fluid inclusions from Kabwe show homogenisation temperatures of 60 to 390°C (Kamona, 1993). At Kipushi, Kengere and Lombe in D. R. Congo, transgressive Zn-Pb-(Cu-Ga-Ge-Mo-As-Ag) mineralization occurring along faults and in breccia fill is hosted by the Kakontwe cap carbonate above the Grand Conglomerat. Kipushi fluids were reducing, since hydrocarbons ("shungite") are associated with the mineralization (Francotte & Jedwab, 1963), which was deposited at c. 300°C (T_h on fluid inclusions, Kapenda, unpubl. data, in Kampunzu et al., 1998).

REDOX BEHAVIOUR OF Cu, Co, Pb AND Zn

There is abundant geological evidence (e.g. replacement textures, reduction spheroids etc) to indicate that the formation of stratiform ores in the Copperbelt has been influenced by redox reactions involving electron transfer in an aqueous medium. The contrasting redox behaviour of metals such as Cu-Co, as well as Pb-Zn, can explain their segregation in such an environment and the development of metal zonation at a variety of scales. The higher the standard reduction potential (Eh_o) of a metal the more susceptible the species is to being reduced.

$Cu \leftrightarrow Cu^{2+} + 2e^-$ $Eh_o = +0.34V$
$Pb \leftrightarrow Pb^{2+} + 2e^-$ $Eh_o = -0.13V$
$Co \leftrightarrow Co^{2+} + 2e^-$ $Eh_o = -0.28V$
$Zn \leftrightarrow Zn^{2+} + 2e^-$ $Eh_o = -0.76V$

The contrasting characteristics of Cu and Co are illustrated in the redox reactions above and also illustrated in Figure 1. It is clear that progressive reduction will first result in the precipitation of Cu from an aqueous solution, followed under more reducing conditions by Co. Superposition of oxic and anoxic fluid fields on the Eh-pH diagram in Figure 1 shows that Cu and Co complexes are relatively soluble under oxic conditions but are less stable under reducing conditions.

The effects of mixing an oxidized, metal-charged fluid with a more reducing liquid such as an oilfield brine have been modelled by Metcalfe et al. (1994) who showed that addition of even a small proportion of the latter will, after only 5% mixing, dramatically change the redox state and promote the sequential precipitation of, first Cu, and then Pb and Zn (once all the Cu had effectively been stripped from solution Figure 2). Although data is not available for Co, the sequence is consistent with the paragenetic characteristics of SSC deposits in general.

GLOBAL ANOXIA AND THE FORMATION OF COPPERBELT STRATIFORM ORES?

Stratiform Cu-Co mineralization in the Copperbelt is generally regarded as being early-to-late diagenetic in its timing. Widely accepted models for the formation of SSC ores (Unrug, 1988; Jowett, 1986) envisage circulation of oxidized brines through porous continental (often aeolian) arenites that are themselves enriched in detritus from a metal fertile provenance. These fluids scavenge metals that have high solubilites in saline, oxidized and near neutral solutions (such as Cu, Co, U, Ni etc), with precipitation of metals occurring as they encounter environments where redox reactions take place (i.e. in the presence of diagenetic sulphides, organic rich sediments etc). Two scenarios exist, that are not mutually exclusive; (i) scavenging of metals by a *single oxidized fluid* passing through permeable strata with lateral precipitation of ores in the proximity of more reduced facies (Bechtel et al., 2002); or (ii) the mingling of *two fluids* in a single aquifer, one a pregnant oxidized solution and the other a reduced barren one (e.g., Bartholomé et al., 1972). Our initial fluid inclusion work suggests that the earliest fluids recorded (e.g. from Chambishi Mine) are characterized by low homogenization temperatures (T_h = 130 to 160°C) and constant high salinity (23 wt.% eNaCl; H_2O-NaCl-CO_2±CH_4) fluid compositions that are potentially diagenetic in origin. Later syn- to post-orogenic fluids (e.g. Nchanga and Nkana Mines) are more diverse in composition and typically have higher homogenization temperatures.

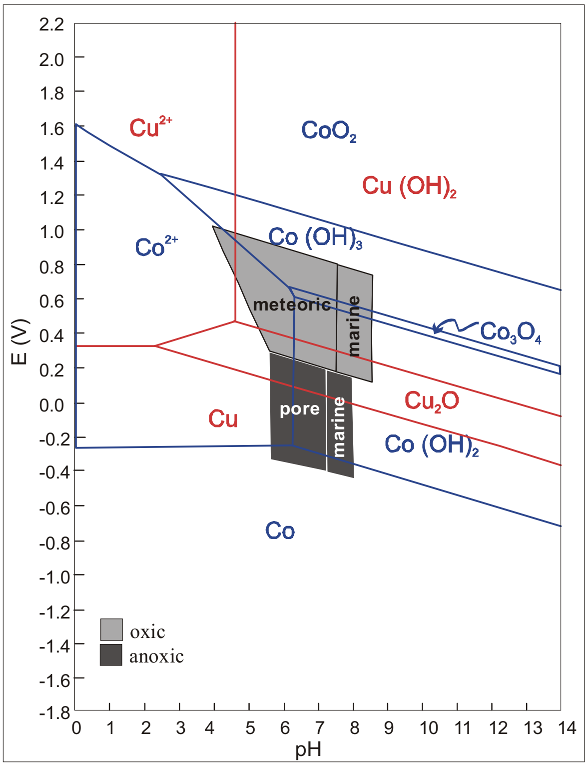

Figure 1: Potential - pH diagram for Cu and Co in the system Cu-Co-H_2O at 25°C (after de Zoubov et al., 1980, and Deltombe, 1980).

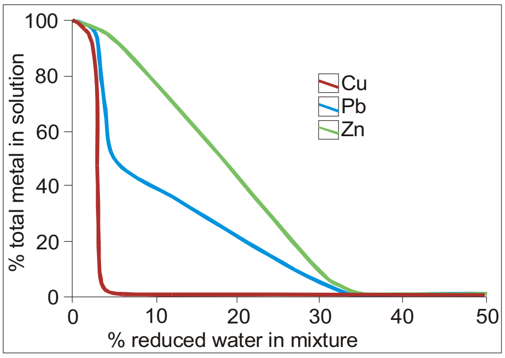

Figure 2: Fluid-rock equilibrium model showing the effect on Cu, Pb, and Zn solubility of mixing a reduced connate fluid with an oxidized metal-laden, diagenetic pore fluid (after Metcalfe et al., 1994).

In the ore genetic scenario involving the mixing of two fluids, the oxidised, metal-bearing fluid is generally thought to be a saline basin brine which became oxidising and chloride and sulphate enriched through reaction with red beds and evaporites. The reduced fluid is generally thought to be expelled into aquifers from the compaction of reduced organic-rich sediments. In the Katangan basin, oxidised brines could have evolved through reaction with the abundant evaporites in the upper Roan Group. We suggest that the reduced fluids responsible for Pb-Zn mineralization, and for some of the Cu-Co mineralization in the two-fluid mixing model (e.g. at Shituru), could have been derived from the adundant black shales in the Mwashya Group, which were deposited during global anoxia coinciding with Snowball Earth conditions.

CONCLUSIONS

Although the conceptual notions regarding fluid mixing and metal deposition in SSC deposit environments are not new, they receive added credibility with respect to the Central African Copperbelt in the light of the new Cryogenian age constraints for Katangan deposition and preliminary fluid inclusion characteristics of ore bearing fluids. Confirmation of such a link with respect to the stratiform Cu-Co ores will need to be rigorously tested by obtaining accurate age determinations for the mineralization events.

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Recent developments in the Central African Copperbelt: geological, geochronological and metallogenic perspectives

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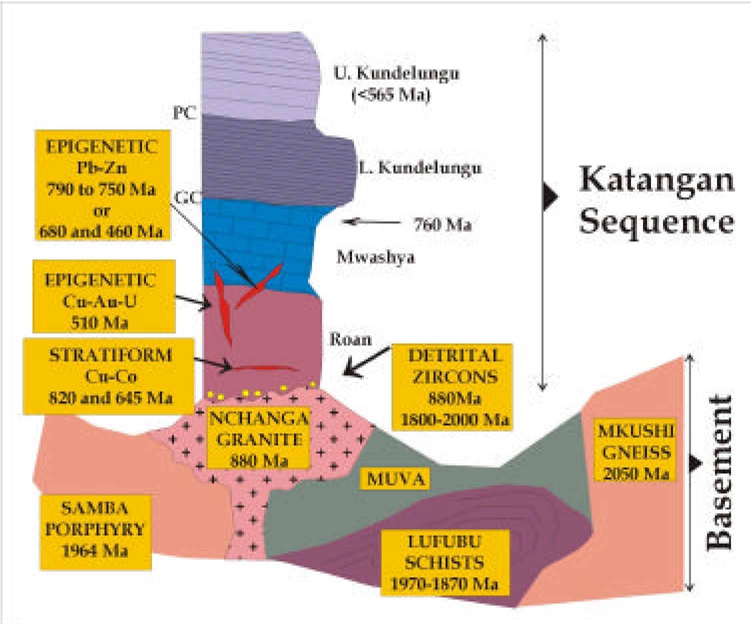
The Central African Copperbelt is one of the world's great metallogenic provinces. The socio-political dynamics of the region have impacted detrimentally on its infrastructure and production record. Re-privatization over the past few years has stimulated a resurgence in geological research in the region, with input from many countries including the US and UK, Australia, Botswana and South Africa, as well as increased local activity in the Democratic Republic of the Congo (DRC) and Zambia. This paper emphasizes the work that has been carried out mainly over the past 6 years at EGRI-HAL, University of the Witwatersrand.

The Katangan sequences, up to 10 km thick and extending over large parts of Zambia and the DRC, have traditionally been subdivided into the Roan, Lower Kundelungu and Upper Kundelungu Supergroups. The Roan Supergroup in Zambia unconformably overlies a deformed, largely Paleoproterozoic, basement, and consists of continental clastics in the lower part (deposited in alluvial fan, braided stream, aeolian dune, and playa flat environments), and evaporitic carbonates, sandstones, siltstones and dolomitic shales, deposited in restricted marine or sabkha environments, in the upper part. The majority of the stratiform Cu-Co mineralization in the Central African Copperbelt occurs within a variety of lithotypes in the lower Roan. The Mwashya Group of the upper Roan comprises mainly carbonate and black shale, together with a number of regionally extensive mafic pyroclastic deposits. These volcanic rocks, which also host Cu mineralization at Shituru, are interbedded with iron-formations. Mwashya sediments are conformably overlain by the Lower and Upper Kundelungu Supergroups, both of which have glacial diamictites at their respective bases, known as the Grand Conglomerat (GC) and Petit Conglomerat (PC) respectively. The GC is interpreted as a fluvio-glacial tillite comprising unsorted, variably sized fragments (occasionally up to 0.3m diameter) of granite, shale, dolomite and quartzite in a clayey matrix. It is overlain by an equally extensive cap carbonate unit known as the Kakontwe limestone which is usually intercalated with shale. The Kakontwe limestone hosts the epigenetic Zn-Pb-Cu-(Ge-Ga) mineralization at Kabwe, Kipushi, Kengere and Lombe, as well as the Cu-Au ores at Kansanshi. The PC, at the base of the Upper Kundelungu Supergroup, is not well preserved in the Zambian portion of the Copperbelt, but outcrops regionally in the DRC. This tillite is thinner than its underlying equivalent (typically 30-50m thick) and contains the same variety of clasts but generally smaller (up to 3cm). It too is overlain by a cap carbonate unit known as the "calcaire rose", or Kalule carbonate sequence.

The basement rocks to the Katangan sequence in the Central African Copperbelt are dominated by a fertile Palaeoproterozoic magmatic arc, in addition to less voluminous Mesoarchaean and Neoproterozoic granitoids (Rainaud et al., 2002a). The calc-alkaline Lufubu metavolcanics yield an age range between 1870 to

1970 Ma, with associated granites having been emplaced in the span 2050 – 1950 Ma. These rocks represent a period of extended, probably episodic, magmatism and deformation that is analogous to the Eburnian orogeny elsewhere in Africa.

Recent reappraisal of the sedimentation and tectonic setting of the Katangan basin suggests that the traditional stratigraphic nomenclature requires modification. Katangan sedimentation was initiated by an early phase of intracontinental rifting which evolved into a proto-oceanic rift; in its latter stages the Katangan sediments may have been deposited in a foreland basin setting associated with severe crustal shortening that arose during collision of the Kalahari and Congo cratons (Wendorff, 2001).



We have recently provided U-Pb zircon geochronological constraints indicating that the Roan Group was deposited between 880 Ma (the age of the Nchanga granite and detrital zircons in the lower Roan sediments) and 760 Ma (a volcanic unit in the Mwashya Group just below the GC; Key et al., 2001). A maximum age of the Upper Kundelungu (Plateau Group) sediments is provided by Ar-Ar ages of detrital muscovite of 565 Ma (Master et al., 2002). The Katangan sequence was, therefore, deposited episodically over an extended period (around 300 million years) of geological time. The two glacial diamictite units in the Katangan sequence, the Grand Conglomerat (GC) and Petit Conglomerat (PC) at the respective bases of the Lower and Upper Kundelungu Supergroups (now included in the Guba Group, Wendorff, 2001), are bracketed between 760 Ma and 565 Ma and are, therefore, possible correlatives of the Chuos/Kaigas/Sturtian (at circa 750-700 Ma) and the Numees/Marinoan (at circa 600 Ma) glaciogenic deposits in Namibia and elsewhere in the world.

The Katangan Sequence is variably deformed and metamorphosed. The highly deformed, thrust-bound, amphibolite grade sedimentary packages of the DRC give way to autochthonous, greenschist facies sediments further south (Kampunzu and Cailteux, 1999). At least two periods of deformation have affected the Katangan sediments during Pan-African orogenesis. This deformation is known locally as the Lufilian orogeny and was also episodic and, although poorly constrained, occurred between about 700 Ma and 500 Ma (Cosi et al., 1992; Rainaud et al., 2002b). The youngest portions of the Upper Kundelungu Supergroup, preserved in the

Kundelungu plateau north of the Copperbelt, are largely unaffected by the Lufilian deformation. New U-Pb dating of monazite and step-heating $^{40}Ar/^{39}Ar$ plateau ages of biotite and K-feldspar in the Copperbelt itself indicate that metamorphic overprints were long-lived and episodic, extending from 590 to 510 Ma (Rainaud et al., 2002b). The latter age at least is implicated in widespread, epigenetic Cu-Au-U mineralization in the Katangan rocks, such as at Kansanshi and Musoshi (Torrealday et al., 2000; Richards et al., 1988).

Stratiform mineralization in the Central African Copperbelt consists of disseminated copper and cobalt sulphide minerals (chalcocite, bornite, chalcopyrite, carrolite) occurring as dispersed grains, fracture fillings, near massive lenses and replacements of diagenetic pyrite, Fe-Ti detrital minerals and micaceous silicates. The sedimentary host rocks mainly form part of the lower Roan Supergroup, although in at least one situation at Shituru Mine, stratiform mineralization is hosted by reduced volcaniclastic rocks in the Mwashya Group. Pb-Zn-(V-Ga-Ge-Cd-Ag) mineralization in the Katangan sequences is epigenetic, and occurs in transgressive orebodies hosted in two different stratigraphic units. At Kabwe, Zambia, Pb-Zn mineralization in pipe-like bodies is hosted by carbonate rocks correlated with the Upper Roan Group. At Kipushi, Kengere and Lombe in DRC, transgressive Zn-Pb-(Cu-Ga-Ge-Mo-As-Ag) mineralization occurring along faults and in breccia fill is hosted by the Kakontwe cap carbonate above the GC. Fluid inclusion studies indicate the presence of at least 2 distinct mineralizing solutions, which is consistent with the variable mineralization styles and long-lived paragenetic sequence in the Copperbelt.

It is now widely accepted that the Cryogenian Period (850-650 Ma) was characterized by at least 2, but perhaps up to 4, near global ice ages (Hoffman and Schrag, 2000; Kirschvink et al., 2000). The “snowball earth” hypothesis suggests that a runaway albedo feedback led to near global low-latitude and low-altitude ice cover causing a virtual shut-down of biogenic activity and the hydrological cycle Neoproterozoic Rapitan-type iron-formations formed in environments where fluctuations in near-surface redox states were caused by these climatic extremes. Given that the solubilities of Cu, Co, Pb and Zn complexes in aqueous solution are redox sensitive, the question of environmental/climatic controls on the oxidative state of the near surface are perhaps also likely to be relevant to ore genetic considerations for the stratiform ores of the Central African Copperbelt. There are few if any accurate age data constraining the timing of stratiform Cu-Co mineralization in the Copperbelt. A K-Ar age of 870±42 Ma (Cahen et al., 1984) for a microcline vein cutting stratiform ore is widely quoted, as is the range between 790 Ma and 750 Ma provided by Pb-Pb model ages for Pb-Zn mineralization from several deposits in the region (Kampunzu et al., 1998). Richards et al. (1988) provided a Pb-Pb model age of 645±15 Ma for Cu-Fe sulphides from the Musoshi Mine, a date interpreted as reflecting either primary ore deposition or Pb re-homogenization. Walraven and Chabu (1991) obtained a Pb model age of 823 Ma for Kinsenda copper sulphide mineralization. Given the long-lived depositional (and diagenetic) history of the Katangan sequences, it is clear that accurate and precise age data are required in order to date the ages of both stratiform Cu-Co and epigenetic Zn-Pb-(Cu-Ga-Ge-Ag) mineralization. The available age constraints are not inconsistent with a broad overlap between periods of global glaciation and mineralization in the Katangan sequences. The notion that a snowball earth type freeze over with its associated near surface redox fluctuations has important metallogenic implications in the Copperbelt is an intriguing one, and warrants more research and resolution in terms of ore genesis models and geochronometry.

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Chronological constraints on the genesis of stratiform Cu-Co mineralization in the Katangan of central Africa and implications for models of ore formation

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Evidence for continental glaciation is found in mid- and late Neoproterozoic successions worldwide. At present it is unclear how many glaciations occurred during the Neoproterozoic era or whether these events were truly global in extent, although evidence does exist for low-latitude deposits in some parts of the world. Global stratigraphic correlations are consistent with, but not yet proof of, two major phases of wide-spread glaciation, one mid-Neoproterozoic phase (often correlated with the 'Sturtian' event) at ca. 730 ± 15 Ma and a younger phase (generally referred to as the 'Marinoan') at ca. 580 ± 10 Ma. The earlier mid-Neoproterozoic glacial episode commonly comprises two major diamictite-mudstone sequences, which have been interpreted as glacial advance-retreat cycles. Banded iron-formations are frequently associated with, but are not unique to, this mid-Neoproterozoic episode of glaciation. Rapitan type iron-formations point to stratified oceanic conditions in the Cryogenian Period in which ferric iron and silica were precipitated at a redox interface in much the same way as characterized the Palaeoproterozoic.

We have recently provided U-Pb zircon geochronological constraints Master et al., 2002) indicating that the Roan Group was deposited between 880 Ma (the age of the Nchanga granite and detrital zircons in the lower Roan sediments) and 760 Ma (a volcanic unit just below the Grand Conglomerat at the base of the Guba or Lower Kundelungu Supergroup; Key et al., 2001). A maximum age of the Upper Kundelungu (Plateau Group) sediments is provided by Ar-Ar ages of detrital muscovite of 565 Ma (Master et al., 2002). The Katangan sequence was, therefore, deposited episodically over an extended period (probably around 300 million years) of geological time. The two glacial diamictite units in the Katangan sequence, the Grand Conglomerat (GC) and Petit Conglomerat (PC) at the respective bases of the Lower and Upper Kundelungu Supergroups (now included in the Guba Group, Wendorff, 2001), are bracketed between 760 Ma and 565 Ma and are, therefore, possible correlatives of other mid- to late-Neoproterozoic glaciogenic deposits elsewhere, such as the Sturtian/Chuos/Kaigas (at circa 730 Ma) and the Marinoan/Varangian/Numees (at circa 580 Ma). Both glaciogenic horizons are characterized by immediately overlying cap carbonate units. Magnetite- and haematite-rich BIF units (with minor Mn) just below the GC are possible correlatives of the Rapitan, Urucum and Damara iron formations and reflect redox stratification in the oceans at this time. Evidence that this interval of sedimentation was deposited during a period of major climatic perturbation comes from preliminary carbon isotope data, which show a negative excursion in ä^{13}C in the Mwashya, decreasing from a value of +2.8 permil V-PDB, going to a minimum of –5 permil in the Grand Conglomerat, and recovering to more positive values (up to +5.3 permil) in the overlying Kakontwe cap carbonates. These data are similar to global carbon isotope excursions related to other Neoproterozoic glaciations (Hoffman & Schrag, 2000).

There are few if any accurate age data constraining the timing of stratiform Cu-Co mineralization in the Copperbelt. A K-Ar age of 870±42 Ma (Cahen et al., 1984) for a microcline vein cutting stratiform ore is widely quoted, as is the range between 790 Ma and

750 Ma provided by Pb-Pb model ages for Pb-Zn mineralization from several deposits in the region (Kampunzu et al., 1999). A different model interpretation of the same data, however, resulted in apparent ages of 680 Ma for Kabwe mineralization, and 456±18 Ma for the Kipushi deposit (Kamona et al.,1999; Walraven & Chabu 1994). Richards et al. (1988a,b) provided a Pb-Pb model age of 645±15 Ma for Cu-Fe sulphides from the Musoshi Mine, a date interpreted as reflecting either primary ore deposition or Pb re-homogenization. Walraven and Chabu (1991) obtained a Pb model age of 823 Ma for Kinsenda copper sulphide mineralization. The model dependant nature of much of the above data is such that there are effectively no absolute age constraints on the timing of stratiform mineralization in the Copperbelt. If, however, ore genesis is related to diagenetic processes, as is generally thought to be the case for this style of deposit, it is likely that the age of mineralization will broadly coincide with that of deposition. However, given the long-lived depositional history of the Katangan sequences, it is clear that diagenetic processes in the succession will be diachronous and became progressively younger upwards in the stratigraphy. Accordingly, diagenetic fluid flow and related stratiform Cu-Co mineralization in the lower Roan sediments are likely to be older than similar styles of ore deposition in the upper Roan or Mwashya sequences.

Stratiform mineralization in the Copperbelt consists of disseminated copper and cobalt sulphide minerals (chalcocite, bornite, chalcopyrite, carrolite) occurring as dispersed grains, fracture fillings, near massive lenses and replacements of diagenetic pyrite, Fe-Ti detrital minerals and micaceous silicates. The sedimentary host rocks mainly form part of the lower Roan Supergroup, but comprise a wide range of lithotypes, including basal continental clastics and aeolianites, shales and siltstones, evaporitic carbonates, dolomitic shales and stromatolitic bioherms. Much of the mineralization is linked to the 'Ore Shale', that was formed in a restricted marine or lacustrine environment, although mineralization does occur in other lithotypes higher up in the succession. In at least one situation at Shituru Mine, for example, stratiform mineralization is hosted by reduced volcaniclastic rocks in the Mwashya Group.

Ore genesis in stratiform sediment hosted copper (SSC) deposits is typically related to diagenetic processes where saline, oxidized, near-neutral connate waters scavenge redox-sensitive metals such as Cu, Co, U, Ni etc. Precipitation of these metals occurs when the pregnant solutions interact, either with another more reduced fluid, or with a reduced sediment elsewhere in the succession. The onset of periodic intervals of anoxia related to near-global ice-ages (the 'Snowball Earth', Hoffman & Schrag, 2000) may have contributed to ore formation by providing basin-wide, but stratigraphically localized, reducing environments that controlled metal precipitation. Re-Os isotope dating of stratiform sulphides from Nchanga and Mufulira mines in Zambia, currently in progress, will hopefully provide actual constraints on the timing of mineralization and shed light on its relationship to glaciogenic events in the basin.

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TIMING OF Cu-Co and Pb-Zn MINERALIZATION IN THE CENTRAL AFRICAN COPPERBELT: A LINK TO NEOPROTEROZOIC GLACIATIONS?

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Introduction:
Evidence for low-latitude continental glaciation is found in mid- and late Neoproterozoic successions worldwide. Global stratigraphic correlations are consistent with, but not yet proof of, two major phases of wide-spread glaciation, one mid-Neoproterozoic phase (often correlated with the 'Sturtian' event) at ca. 730 ± 15 Ma and a younger phase (generally referred to as the 'Marinoan') at ca. 580 ± 10 Ma. Rapitan type banded iron-formations are frequently associated with, but are not unique to, the earlier episode of glaciation. They point to stratified oceanic conditions in the Cryogenian Period in which ferric iron and silica were precipitated at a redox interface.

Age constraints:
We have recently provided geochronological constraints indicating that the Katangan sequences that host the vast stratiform Cu-Co and epigenetic Pb-Zn deposits of the Central African Copperbelt are midNeoproterozoic to Cambrian in age (Master et al., 2002). The lowermost Roan Group was deposited between 880 Ma (the age of the Nchanga granite and detrital zircons in the lower Roan sediments) and 760 Ma (a volcanic unit just below the Grand Conglomerat at the base of the Guba or Lower Kundelungu Supergroup; Key et al., 2001). A maximum age of the Upper Kundelungu (Plateau Group) sediments is provided by Ar-Ar ages from detrital muscovite of 565 Ma. The Katangan sequence was, therefore, deposited episodically over an extended period (about 300 million years) of geological time (Figure 1). The two glacial diamictite units in the Katangan sequence, the Grand Conglomerat (GC) and Petit Conglomerat (PC) at the respective bases of the Lower and Upper Kundelungu Supergroups (now included in the Guba Group, Wendorff, 2001), are bracketed between 760 Ma and 565 Ma and are, therefore, likely correlatives of the Sturtian and Marinoan glaciogenic deposits. The two glaciogenic horizons are characterized by cap carbonate units immediately overlying them. Magnetite- and haematite-rich BIF units (with minor Mn) below the GC in the Mwashya are correlated with similar iron formations in the Rapitan, Urucum, Damara and other sequences worldwide.

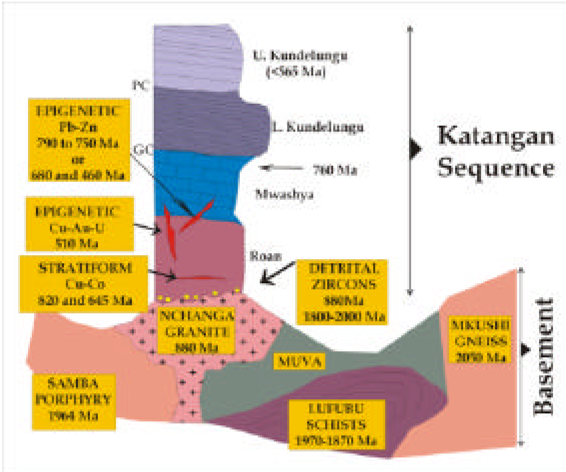

Figure 1. Simplified geological and age relationships in the Zambian portion of the Central African Copperbelt

Mineralization:
Stratiform mineralization in the Copperbelt consists of disseminated copper and cobalt sulphide minerals (chalcocite, bornite, chalcopyrite, carrolite) occurring as dispersed grains, fracture fillings, near massive lenses and replacements of diagenetic pyrite, Fe-Ti detrital minerals and micaceous silicates. The sedimentary host rocks mainly form part of the lower Roan Supergroup and comprise a wide range of lithotypes. Much of the mineralization is linked to the 'Ore Shale', that was formed in a restricted marine or lacustrine environment, although many other sediment types are also mineralized. In at least one situation at Shituru Mine, stratiform mineralization is hosted by reduced volcaniclastic rocks in the overlying Mwashya Group. Unrug (1988) has emphasized the fact that stratiform Cu-Co mineralization is distributed throughout the Roan Supergroup but does not occur above the GC, into the Kundelungu sequences. Different scales of mineral zonation are evident in the district and, in general, there is metal segregation into Cu, Cu-Co and Pb-Zn rich zones. Pb-Zn mineralization in the Katangan is epigenetic, and occurs in transgressive orebodies hosted in two different stratigraphic units. At Kabwe, Zambia, Pb-Zn-(V-Ga-Ge-Cd-Ag) mineralization in pipe-like bodies is hosted by carbonate rocks correlated with the Upper Roan Group. At Kipushi, Kengere and Lombe in the DRC,

transgressive Zn-Pb-(Cu-Ga-Ge-Mo-As-Ag) mineralization occurring along faults and in breccia fill is hosted by the Kakontwe cap carbonate above the GC. An interesting feature of many Pb-Zn deposits in Neoproterozoic sedimentary sequences, such as Kabwe in Zambia, Kipushi in the DRC and Skorpion in Namibia, as well as in other parts of the world such as Beltana in the Adelaidean of South Australia and Vazante in Brazil, is the presence, in addition to sphalerite, of non-sulphide zinc minerals (mainly willemite). Such mineralization is attributed to unusually high fO_2 and low fS_2 fugacities during first deformation of the host sediments, an event that at least in Africa and Brazil, occurred at about 680-650 Ma (Large, 2001).

There are few if any accurate age data constraining the timing of either stratiform Cu-Co or epigenetic Pb-Zn mineralization in the Copperbelt. An age range of 790 Ma to 750 Ma is suggested by Pb-Pb model ages for Pb-Zn mineralization from several deposits in the region (Kampunzu et al., 1998). However, Kamona et al. (1999) reinterpreted these data and suggested ages of 680 Ma for Kabwe and 460 Ma for Kipushi mineralization. Richards et al. (1988) provided a Pb-Pb model age of 645±15 Ma for Cu-Fe sulphides from the Musoshi Mine, a date interpreted as reflecting either primary ore deposition or Pb re-homogenization. Walraven and Chabu (1994) obtained a Pb model age of 823 Ma for Kinsenda copper sulphide mineralization. Given the long-lived depositional and tectonic histories of the Katangan sequences, it is likely that mineralization was grossly diachronous, representing different episodes in the geological evolution of the region.

Metallogenesis and the Snowball Earth:

Ore genesis in stratiform sediment hosted copper (SSC) deposits is typically related to diagenetic processes where saline, oxidized, near-neutral connate waters scavenge redox-sensitive metals such as Cu, Co, U, Ni and Ag from sediments towards the base of a succession. Precipitation of these metals occurs when the pregnant solutions interact, either with another more reduced fluid, or with a reduced sediment higher up in the succession. Fluid inclusion studies in the Copperbelt indicate the presence of at least 2 distinct mineralizing solutions, which is consistent with a fluid mixing model for precipitation of metals over a long-lived paragenetic sequence. The onset of periodic intervals of anoxia related to near-global ice-ages (the 'Snowball Earth', Hoffman & Schrag, 2000) may have contributed to ore formation by providing basin-wide, but stratigraphically localized, reducing environments that controlled metal precipitation. The 'hot-house' rebound that characterized the aftermath of global glaciation may have been responsible for the highly oxidative conditions that resulted in the subsequent formation of widespread non-sulphide (willemite) mineralization in associated Pb-Zn deposits. It is conceivable that some of the secondary copper mineralization (malachite, chrysocolla etc) so characteristic of the Copperbelt might also be linked to this event, although much of it is undoubtedly much later. Re-Os isotope dating of stratiform sulphides from Nchanga, Chambishi and Mufulira mines in Zambia, currently in progress, will hopefully provide more accurate constraints on the timing of mineralization and shed light on its relationship to glaciogenic events in the basin.

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Fluid inclusion characteristics of the Copperbelt, and overview of Katangan geochoronology

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INTRODUCTION

The stratiform ores of the Zambian and Democratic Republic of the Congo (DRC) Copperbelt are hosted by the metasediments of the Katangan sequence. This sedimentary succession overlies a Mesoarchaean to Neoproterozoic basement, which is composed of the metavolcanics of the Lufubu schists, the metasediments of the Muva Sequence, and various granitoids mainly intruding the Lufubu schists (Rainaud et al. 2003a,b; Armstrong et al. 2003). The Nchanga Granite is the youngest intrusion in the pre-Katangan basement and has been dated with certainty with the U-Pb SHRIMP technique at 877±11Ma (Armstrong et al. 2003).

Current lithostratigraphic practice in the DRC is to subdivide the Katanga Supergroup into the Roan, Nguba (ex-Lower Kundelungu) and Kundelungu (ex-Upper Kundelungu) Groups. Recently, Wendorff (2001; 2003a,b) has proposed a new lithostratigraphic scheme, in which the Katanga Supergroup is subdivided into the Roan, Guba and Kundelungu Groups, with two additional lithotectonic units, the Fungurume and Biano Groups, which were deposited syntectonically in a foreland basin during deformation of the earlier Katangan groups during the Pan-African Lufilian orogeny.

Age constraints on the deposition of this sedimentary sequence are still scarce. Detrital zircons from the Lower Roan yielded two groups of ages: one at around 2-1.8 Ga corresponding to the age of the Palaeoproterozoic basement, and another at around 880 Ma corresponding to the age of the Nchanga granite, therefore showing that the Katangan sedimentary sequence is younger that this intrusion. In western Zambia, volcanics within the Mwashya Subgroup (Nguba Group), have been dated at 760 ± 5 Ma, utilising SHRIMP U-Pb dating on zircons (Key et al., 2001). Recent dating by Barron et al. (2003) of two gabbroic bodies in the Solwezi area, NW Zambia, yielded ages of 745 ± 7.8 Ma and 752.6 ± 8.6 Ma, which are consistent with them being part of the extensional mafic magmatism associated with the Mwashya Subgroup (e.g., Kabengele et al., 2003).

To the southeast of the Mwinilunga (NW Zambia) area, strongly deformed and poorly differentiated Katangan rocks of the West Lunga Formation have been provisionally correlated with the Lower Kundelungu Supergroup (Liyungu et al., 2001), which corresponds to the upper part of the Nguba Group above the Grand Conglomerat (i.e., Muombe Subgroup of Wendorff, 2003a,b). One of the porphyritic lavas in this area has been dated with the SHRIMP (U/Pb on single zircons) at 735 ± 5 Ma (Armstrong, 2000; Liyungu et al., 2001). Finally, detrital muscovites from Biano Group siltstones give a maximum $^{40}Ar/^{39}Ar$ age of sedimentation of 570 ± 5 Ma for this group.

MINERALIZATION

Mineralization in the Copperbelt is hosted mainly in shales (Luanshya, Nkana, Chambishi, Chingola, Chililabombwe, Musoshi) and arenites/arkoses (Mufulira, Bwana Mkubwa), of the lower part of the Roan Group. Subsequent metamorphic events (including the Pan African Lufulian orogeny) have led to the remobilisation of primary sulphides. The mineralization is present in the form of copper- (and locally cobalt-) sulphides. Major primary minerals include chalcopyrite, bornite, chalcocite, pyrite, ±carrollite and cobaltiferous pyrite. Secondary alteration minerals include covellite, digenite, tellurobismuthite, molybdenite, and uranium minerals as minor occurrences. Primary sulphide ores are leached and oxidised to copper carbonates (malachite, azurite), native copper, copper oxides (cuprite, tenorite), copper phosphates, copper silicates (chrysocolla), copper sulphates, cupriferous wad, and cupriferous micas (Notebaart & Vink, 1972).

FLUID INCLUSIONS

Fluid inclusion microthermometry and Raman spectroscopy were conducted on samples representing various tectonic settings from selected deposits in the Zambian Copperbelt. This has revealed the presence of diverse fluid types. The reader is referred to Table 1 for a list of properties of the following fluid types.

Authigenic quartz overgrowths

Primary fluid inclusions present in 'dust rims' between quartz grains of the metasediments of the Upper Ore Body at the Nchanga Mine revealed the presence of aqueous (w), and aqueous-carbonic (w-c) fluids generally with included halite daughter crystals (s). These inclusions are small in size, ranging from 6 to 15 μm in diameter.

Pre-tectonic quartz veins

Quartz veins intruded the mineralized metasediments of the Chambishi deposit before folding during metamorphism, as is indicated by field observations of cleavages running through the metasediments. Refracted cleavages are visible in the quartz veins. Mineralization from the sediments laterally secreted into the quartz veins which were subsequently folded together with the sediments. The veins are therefore representative of post-mineralising, pre-deformational fluids. These fluids are divided into three main types, namely aqueous (w), aqueous-carbonic (w-c), and methane-rich (m) inclusions. The aqueous fluids are low- to high salinity $CaCl_2$-NaCl±KCl brines.

Syn-tectonic quartz veins

Quartz veins, representative of pulses of syn-tectonic fluid introduction to the sediments during metamorphism, were sampled from the Chambishi, Nchanga, Nkana, and Mufulira deposits. The aqueous fluids inclusions (w) were found in samples from Nchanga, and correspond to low salinities. Aqueous-carbonic (w-c±s) fluids from Chambishi are relatively saline with CO_2, N_2, CH_4, $\pm C_2H_6$, and H_2. Aqueous-carbonic fluids sampled from Nchanga show CO_2 and N_2 in the volatile phases, with halite daughter minerals. Carbonic-rich inclusions (±w), and methane-rich (m) inclusions (with no H_2O) were also identified. Aqueous inclusions from Nkana contain methane (w-m), whereas aqueous fluids from Mufulira are composed of N_2 in the volatile phases. The Mufulira inclusions are saturated with halite, and some inclusions also contain hematite (he) daughter minerals.

Table 1: Microthermometry and Raman analyses for fluid inclusions from three paragenetic settings of the Zambian Copperbelt (see text for explanation of abbreviations)

		Authigenic	Pre-tectonic	Syn-tectonic
deposit		Nchanga	Chambishi	Chambishi, Nchanga, Nkana, Mufulira
host mineral		quartzites	quartz veins	quartz veins
type		• w ±s • w-c ±s	• w • w-c • m	• w • w-c ±s • c ±w • m • w-n-s ±he
Tm ice (°C)	w	-15.7 to -3.1	-22.1 to -1.6	-7.1 to -6.0
	w-c	-25 to -17	-21.2 to -11.6	-24.0 to -6.4
volatile composition (mol%)		w-c ±s: CO_2: ~97 N_2 ~2.5 CH_4 ~ <0.3	w-c: CO_2: ~98.5 N_2: ~1.3 H_2S: ~<0.5 m: CH_4: ~93 N_2: ~6.5 C_2H_6: ~0.5	w-c ±s -Chambishi CO_2: 32-98 N_2: 1-47 CH_4: 0.3-35 H_2: 14 w-c ±s -Nchanga CO_2: ~97.5 N_2: ~2.5 c (±w) -Nchanga CO_2: ~97.5 N_2: ~2.5 m -Nchanga CH_4: 100 w-m-Nkana CH_4: 84 CO_2: 16 w-n-s ±he -Mufulira N_2: 100

CONCLUSIONS

Microthermometry and Raman spectroscopy reveal the diverse nature of fluids representative of various tectonic settings. Fluid inclusions representative of syn-tectonic processes are more complex in compositions compared to earlier fluids. Fluid inclusions in the authigenic setting may be indicative of fluids preserved during diagenetic processes. However, subsequent fluid infiltration during metamorphic events may also have overprinted fluid inclusions, and/or trapped new inclusions in pre-existing porous zones in the sediments.

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