# PRE- AND POST-KATANGAN GRANITOIDS OF THE GREATER LUFILIAN ARC – GEOLOGY, GEOCHEMISTRY, GEOCHRONOLOGY AND METALLOGENIC SIGNIFICANCE

## Volume 1, Text

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# ABSTRACT

This document reports observations, findings and conclusions of the research project entitled “Pre- and Post-Katangan Granitoids of the Greater Lufilian Arc - Geology, Geochemistry, Geochronology and Metallogenic Significance”. The project, structured and supervised by Professor Laurence Robb, was designed to study granitoids that comprise the Greater Lufilian Arc. Its main aims were to define the various granitoids, and study their role in Katangan orogenesis and mineralization. Main fieldwork was concentrated in northwestern Zambia and northern Namibia.

The Greater Lufilian Arc is a curvilinear belt of Neoproterozoic Katangan sediments that was deformed during the Pan African orogeny in Zambia and the Democratic Republic of Congo, and the westward extension of similar rock sequences into Botswana, Angola and Namibia. The mobile belt of the Greater Lufilian Arc also comprises a dominantly Paleoproterozoic basement of deformed granitoids, and a diverse suite of Pan-African granitoids that intrude the Katangan sequences.

A total of 1500 samples were collected in the field; 351 plutonic rocks were analysed. 157 chemical analysis were compiled from various well-documented sources, to reach a total of 508 samples analysed in the database. 38 new zircon U-Pb SHRIMP II and laser ablation ICP-MS ages were produced.

The majority of intrusive rocks from the Greater Lufilian Arc that were analysed (60%) had midalkaline characte. 33% were subalkaline and 7% were alkaline. Mafic rocks are closely associated to felsic rocks in most domains of the Arc. Two thirds of the gabbroids were midalkaline, 1/6 alkaline and 1/6 subalkaline. The average rock type distribution for the entire Lufilian Arc closely resembles that of the Hook Granite Batholith in Zambia.

A frequent field observation is the persistent clustering of small bodies of red-altered granitoids, gabbroids, massive magnetite-hematite and quartz pods that are linked to ages around 550 and 750 Ma. The four-rock association is related to iron oxide-copper-gold (IOCG) mineralization, and seems to be a characteristic of continental extension anorogenic environments.

Another recurrent feature observed in most outcrops of the study area is the presence of two or more contrasting types of plutonic rocks, including mafic, ultramafic and alkaline plugs and dikes. The multiplicity of rock types in a small area seems to be a characteristic of continental extension anorogenic environments. Quartz pods, hydrothermally-emplaced iron oxide bodies and round-pebble hydrothermal breccias are features that occur often in and around IOCG systems throughout the Greater Lufilian Arc.

The main granitoid periods of emplacement present in the study area of the Arc are listed on Table 1. Several more restricted events occurred at 1700, 1600, 880 and 460 Ma.

***Table 1 Main Granitoid Terranes in the Greater Lufilian Arc***

| Age (Ma) | Rock types | Location | Environment of Emplacement | Notes |
|---|---|---|---|---|
| 550 ±50 | Granite, alkali granite, quartzmonzonite, syenite, gabbroids | Otjiwarongo, central Namibia, Kaokoland, Damaran intrusives (Namibia), Hook Granite, NW Zambia (Zambia) | Continental epeirogenic uplift | The period may be broken into 3 discrete events. |
| 750 ±50 | Granite, alkali granite, syenite and gabbroids with felsic and mafic volcanics | Copperbelt, Kalengwa-Kasempa, NW Zambia (Zambia); Khorixas Inlier and Summas Mountains (Namibia) | Rift-related and continental epeirogenic uplilft. | Intrude Roan and Nguba Lithologies; overlain by Kundelungu and equivalent sediments. |
| 1100 ±50 | Granitoids and felsic to mafic volcanics | South of the Copperbelt, West of Lusaka (Zambia); around Omitiomire, Kaokoland and the Witvlei area (Namibia) | Continental rift-related environments | Surrounds Kapvaal Craton from Namaqualand to Irumide Belt in Zambia |
| 1900 ±100 | Foliated alkali granie, quartzmonzonite and granite | Copperbelt basement, Mkushi-Serenje, NW Zambia, Domes region (Zambia); Kaokoland, central Namibia, Kamanjab Batholith, Grootfontein Inlier (Namibia) | Not well defined; probably formed in an anorogenic continental extension environment | Period can be broken into 4 discrete events |

The Zambian Lufilian Arc and Damara region of Namibia behaved as independent entities from 2200 to 2000 Ma. They also behaved significantly different from 1400 to 850 Ma. Geological history of the two main portions of the Greater Lufilian Arc is consistent from *circa* 800 Ma to the present, and especially during the last 600 million years.

Most areas studied in the Arc show polycyclic geological histories. Repeated anorogenic intrusive events are a common denominator. Prolonged crustal histories have resulted in superimposition of events.

Granitoid rock suites with closely matching chemistry and macroscopic features have been found to form two or three times in the same region, with up to a thousand million years of age difference. These features preclude lithological or detailed geochemical correlation of plutonic rocks.

At least ten clusters of ring complexes were identified in the Arc. Clustering of multiple anorogenic ring complex intrusions can form batholithic size bodies. Clusters are made by amalgamation of multiple ring complexes of varying chemical composition and size. Most of their rocks are midalkaline. Volcanic and plutonic rocks of roughly the same composition occur together. Total duration of ring complex cluster cycles averages 110 Ma, and their plan view geometry is roughly that of an isosceles triangle.

Information currently available on geophysics, geochronology, rock distribution and geochemistry from the Hook Granite Batholith (Zambia) fit quite well with an intracontinental, anorogenic, ring complex cluster origin. The Nchanga Granite (Zambia) has all the characteristics of an anorogenic granite ring complex, and might have contributed to the origin of copper in its environs. Several sources of evidence indicate that the Kamanjab Batholith (Namibia) is an anorogenic cluster of ring complexes. Volcanic and plutonic rocks of similar composition make the batholith. Geological history for the Khorixas Inlier and the Kamanjab Batholith are significantly different.

Complete Wilson cycles were not identified in the study areas of the Greater Lufilian Arc. The dominant magmatic process, as evidenced by the volume of extruded rock, is anorogenic continental epeirogenic uplift, closely-followed in time by a rift-related granitoid emplacement. Coalescing and overprinting aulacogens seem to be the main geological event in the Arc.

Incipient migmatitization and alteration of Paleoproterozoic rocks modified their chemistry to a point where their environment of emplacement cannot be identified by traditional geochemical means.

The anomalous thorium content in some granitoids of the Greater Lufilian Arc induced and maintained long-lived, large convective cells of hydrothermal fluid flow.

E-W-trending regional fracture systems, that run parallel to the elongation of the Arc, play an important role in the emplacement of magmatism and IOCG mineralization. Those structures are generally parallel to the main Lufilian Arc trend, and could have been normal syn-rift faults reactivated multiple times during geological history.

At least eight discrete periods of mineralization were identified in the Greater Lufilian Arc. There is a wide-spread series of midalkaline intrusions emplaced around 750 Ma that produces a variety of mineral deposits. Another event took place around 540±40 Ma. Five less well defined events occurred at ~1970, ~1930, ~1866, 1097-1059 and ~460 Ma. The dominant deposit type is iron oxide-copper-gold mineralization, but other types of mineral deposits are present in the Arc. At least two distinct events of disseminated copper mineralization associated to midalkaline granitoid intrusives were identified in the Kamanjab Batholith; the first took place around 1975 Ma and the second around 1928 Ma.

The main IOCG events that have been identified in the Greater Lufilian Arc took place during eight time periods. The rocks of many IOCG deposits and prospects in the Arc are pristine. There is no significant deformaton involved. Hydrothermal brecciation and other mineralization features are un-deformed.

Three discrete time periods show IOCG mineralization in close temporal spatial association with sedimentary-hosted copper deposits. The first took place around Witvlei (Namibia) from 1108 to 1059 Ma. The second and third ocurred in the basement to the Zambian Copperbelt from 882 to 725 Ma and from 607 to 500 Ma. This idea may generate a new concept for the origin of sedimentary-hosted copper and cobalt deposits.

# 9 CONCLUSIONS

## 9.1 Main Granitoid Terranes in the Greater Lufilian Arc

The nature of the granitoid terranes in the study area of the Greater Lufilian Arc can be summarized as follows:

1. Foliated alkali granite, quartzmonzonite and granite were emplaced at 1900±100 Ma. They are present beneath the Katanga Supergroup in the Copperbelt, the Mkushi-Serenje area, NW Zambia, and the Domes region (Zambia); Kaokoland, central Namibia, the Kamanjab Batholith and Grootfontein Inlier (Namibia). The environment of emplacement for these rocks has not been well identified, but tends to be anorogenic. This period may be broken into at least four discrete events.

2. Generally poorly outcropping pre-Katanga granitoid and felsic to mafic volcanics were emplaced at 1100±50 Ma. They are present south of the Copperbelt, and west of Lusaka (Zambia); around Omitiomire, Kaokoland and the Witvlei area (Namibia). These rocks surround the Kapvaal Craton continuously from Namaqualand in South Africa, to the Irumide Belt in Zambia. They were emplaced in anorogenic continental rift–related environments.

3. Sporadic, but widely distributed, small igneous intrusions were emplaced at 750±50 Ma. They comprise granite, alkali granite, syenite and gabbro with felsic and mafic volcanics, as observed in the Copperbelt, Kalengwa-Kasempa and NW Zambia (Zambia); Khorixas Inlier and Summas Mountains (Namibia). These bodies intrude Roan and Nguba Formation lithologies but are generally overlain by (Upper) Kundelungu sediments and their Namibian equivalents. They were emplaced in anorogenic rift-related and continental epeirogenic uplift environments.

4. Widespread and voluminous granitoid magmatism (Pan African) was emplaced at 550±50 Ma. It is well preserved in the environs of Otjiwarongo, central Namibia, Kaokoland, and in west-central Zambia (including the Hook Granite Batholith), but also sporadically detected in NW Zambia. The Otjiwarongo batholith, a covered pluton in Namibia, may be similar to the Hook Granite batholith in size, rock type and age. These rocks were emplaced in continental epeirogenic uplift and rift-related environments. This period may be broken into at least three discrete events.

5. Several, more restricted magmatic events occur during the last 2000 Ma in the Greater Lufilian Arc. Examples of this are the Nchanga Granite in Zambia (880 Ma); magmatism at 1700 Ma in the Khorixas Inlier, Namibia; and at 1600 in the Kamanjab Batholith.

The Zambian Lufilian Arc and Damara region of Namibia behaved in a different way from 2200 to 2000 Ma; they were independent entities. They also behaved significantly different from 1400 to 850 Ma. Geological history of the two main portions of the Greater Lufilian Arc is consistent from *circa* 800 Ma to the present, and especially during the last 600 Ma.

## 9.2 Polycyclic Geological History

Most areas studied in the Greater Lufilian Arc show polycyclic geological histories. Repeated anorogenic intrusive events are a common denominator. Source rocks for the various melts come from previously-formed intrusive rocks and siliciclastics. Prolonged crustal histories have resulted in superimposition of events. Two Namibian examples illustrate this. In the Otjiwarongo environs, Neoproterozoic granites intruded anorogenic Paleoproterozoic granites, and both were intruded almost in the same location by two large Mesozoic alkaline complexes. At the Oas farm, a Mesozoic mafic feeder pipe cuts through 750 Ma alkaline intrusions that had intruded Paleoproterozoic anorogenic granitoids. Melts and sedimentary rocks have been re-worked in each of the areas; a lot of magma mixing and crustal contamination processes were involved in the formation of the granitoids.

## 9.3 Rock Types

The majority of the rocks from the Greater Lufilian Arc that were analysed had midalkaline character. Table 9.1 compiles statistics on sample composition and alkalinity that were carried out in all sampling domains. Any rock that plotted outside of the fields of the modified TAS diagram was not included in the statistics.

***Table 9.1 Rock type statistics of all samples analysed from the Greater Lufilian Arc***

| Group | Rock type | number | % | Granitoids | Groups |
|---|---|---|---|---|---|
| **Midalkaline Rocks** | Alkali granite | 102 | 22.13 | 63.93 | 59.87 |
| | Quartzmonzonite | 83 | 18.00 | | |
| | Syenite | 32 | 6.94 | | |
| | Monzonite | 17 | 3.69 | | |
| | Monzodiorite | 10 | 2.17 | | |
| | Monzogabbro | 12 | 2.60 | | |
| | Alkali gabbro | 20 | 4.34 | | |
| **Subalkaline Rocks** | Granite | 99 | 21.48 | 36.07 | 32.75 |
| | Granodiorite | 33 | 7.16 | | |
| | Diorite | 6 | 1.30 | | |
| | Gabbro-diorite | 3 | 0.65 | | |
| | Quartzolite | 4 | 0.87 | | |
| | Gabbro | 6 | 1.30 | | |
| **Alkaline Rocks** | foid syenite | 11 | 2.39 | | 7.38 |
| | foid monzosyenite | 4 | 0.87 | | |
| | foid monzo-diorite | 2 | 0.43 | | |
| | foid gabbro | 12 | 2.60 | | |
| | Foidolite | 3 | 0.65 | | |
| | Peridot gabbro | 2 | 0.43 | | |
| **Total** | | 461 | 99.57 | 100.00 | 100.00 |
| | Carbonatite | 10 | | | |
| **Total including carbonatites** | | 471 | | | |

The database of 471 samples was broken into domains as indicated on Table 9.2. Rock type percentages for each domain is listed on Table 9.3.

***Table 9.2 Number of samples from each rock type for domains of the Greater Lufilian Arc.***

| Rock type/ Region | Hook Granite | NW Zambia | Copperbelt | Kamanjab | Khorixas | Okwa,Ugab,Summas,Grootf | Otjiwarongo | Okatjepuiko | KalengwaKasempa | West Lusaka Kafue Flats | total | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| alkali granite | 26 | 7 | 6 | 26 | 10 | 4 | 13 | 1 | 2 | 7 | 102 | **Midaldaline** |
| quartzmonzonite | 20 | 8 | 5 | 38 | 1 | 1 | 5 | | 3 | 2 | 83 | |
| syenite | 7 | 2 | 2 | 3 | 9 | 1 | 2 | | 2 | 4 | 32 | |
| monzonite | 5 | 1 | 1 | 2 | 2 | | 2 | 2 | 2 | | 17 | |
| monzodiorite | 3 | 1 | 2 | 1 | | | | | 3 | | 10 | |
| monzogabbro | 1 | 1 | 3 | 1 | 1 | | | 1 | 3 | 1 | 12 | |
| alkali gabbro | 2 | 5 | 1 | 3 | 3 | | | 1 | 3 | 2 | 20 | |
| granite | 16 | 10 | 15 | 22 | 8 | 11 | 7 | 5 | 1 | 4 | 99 | **Subalkaline** |
| granodiorite | 7 | 8 | 8 | 3 | 1 | 1 | | 1 | 1 | 3 | 33 | |
| diorite | | 1 | 2 | | | | 1 | | | 2 | 6 | |
| gabbro-diorite | 1 | | | | 1 | | | | | 1 | 3 | |
| quartzolite | | | | 3 | | | 1 | | | | 4 | |
| gabbro | 1 | 1 | 1 | 1 | 1 | | | | | 1 | 6 | |
| foid syenite | | 8 | 1 | 2 | | | | | | | 11 | **Alkaline** |
| foid monzosyenite | | | | | 4 | | | | | | 4 | |
| foid monzo-diorite | | | 1 | | | | | | 1 | | 2 | |
| foid gabbro | | 2 | 2 | | 1 | | | | 7 | | 12 | |
| foidolite | | 1 | | 2 | | | | | | | 3 | |
| peridot gabbro | | | | 1 | 1 | | | | | | 2 | |
| carbonatite | 1 | | | | 9 | | | | | | 10 | |
| Total | 90 | 56 | 50 | 108 | 43 | 18 | 31 | 11 | 27 | 27 | 461 | |

***Table 9.3 Percentages of each rock type for domains of the Greater Lufilian Arc.***

| Rock type/ Region | Hook Granite | NW Zambia | Copperbelt | Kamanjab | Khorixas | Okwa,Ugab,Summas,Grootf | Otjiwarongo | Okatjepuiko | KalengwaKasempa | West Lusaka Kafue Flats | Kalene Hill | Nchanga Granite | Muliashi Porphyry | Chambishi | Oas Farm | Lofdal farm | Percentage | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| alkali granite | 29.2 | 12.5 | 12 | 24.1 | 23.3 | 22.2 | 41.9 | 9.09 | 7.14 | 25.9 | 20 | 8.33 | 12.5 | 12.5 | 25.9 | | 22.13 | Midaldaline |
| quartzmonzonite | 22.5 | 14.3 | 10 | 35.2 | 2.33 | 5.56 | 16.1 | | 10.7 | 7.41 | 23.5 | | 25 | | 3.7 | | 18.00 | |
| syenite | 7.87 | 3.57 | 4 | 2.78 | 20.9 | 5.56 | 6.45 | | 7.14 | 14.8 | 3.33 | 16.7 | | | 33.3 | | 6.94 | |
| monzonite | 5.62 | 1.79 | 2 | 1.85 | 4.65 | | 6.45 | 18.2 | 7.14 | | | | | | | 8.33 | 3.69 | |
| monzodiorite | 3.37 | 1.79 | 4 | 0.93 | | | | | 10.7 | | 3.33 | | | | 3.7 | | 2.17 | |
| monzogabbro | 1.12 | 1.79 | 6 | 0.93 | 2.33 | | | 9.09 | 10.7 | 3.7 | | | | 12.5 | 3.7 | | 2.60 | |
| alkali gabbro | 2.25 | 8.93 | 2 | 2.78 | 6.98 | | | 9.09 | 14.3 | 7.41 | | | | 12.5 | 3.7 | | 4.34 | |
| granite | 18 | 17.9 | 30 | 20.4 | 18.6 | 61.1 | 22.6 | 45.5 | 3.57 | 14.8 | 23.3 | 66.7 | 31.3 | 12.5 | 11.1 | 25 | 21.48 | Subalkaline |
| granodiorite | 7.87 | 14.3 | 16 | 2.78 | 2.33 | 5.56 | | 9.09 | 3.57 | 11.1 | 23.3 | | 31.3 | 37.5 | | 8.33 | 7.16 | |
| diorite | | 1.79 | 4 | | | | 3.23 | | | 7.41 | | 8.33 | | | | | 1.30 | |
| gabbro-diorite | 1.12 | | | | 2.33 | | | | | 3.7 | | | | | | 8.33 | 0.65 | |
| quartzolite | | | | 2.78 | | | 3.23 | | | | | | | | | | 0.87 | |
| gabbro | 1.12 | 1.79 | 2 | 0.93 | 2.33 | | | | | 3.7 | 3.33 | | | 12.5 | 7.41 | 16.7 | 1.30 | |
| foid syenite | | 14.3 | 2 | 1.85 | | | | | | | | | | | | | 2.39 | Alkaline |
| foid monzosyenite | | | | | 9.3 | | | | | | | | | | 3.7 | 25 | 0.87 | |
| foid monzo-diorite | | | 2 | | | | | | 3.57 | | | | | | | | 0.43 | |
| foid gabbro | | 3.57 | 4 | | 2.33 | | | | 25 | | | | | | 3.7 | | 2.60 | |
| foidolite | | 1.79 | | 1.85 | | | | | | | | | | | | | 0.65 | |
| peridot gabbro | | | | 0.93 | 2.33 | | | | | | | | | | | 8.33 | 0.43 | |

60%, 33%, 7% is the percentage relationship of midalkaline to subalkaline to alkaline rock groups for the entire project (Fig 9.1). 64%, 36% is the percentage relationship of midalkaline to subalkaline granitoids. Carbonatites make 2.1% of the total samples. If the suite of mafic rocks collected are considered representative of reality, then midalkaline gabbroids make 66%; alkaline gabbroids, 18%; and subalkaline gabbroids, 17%.

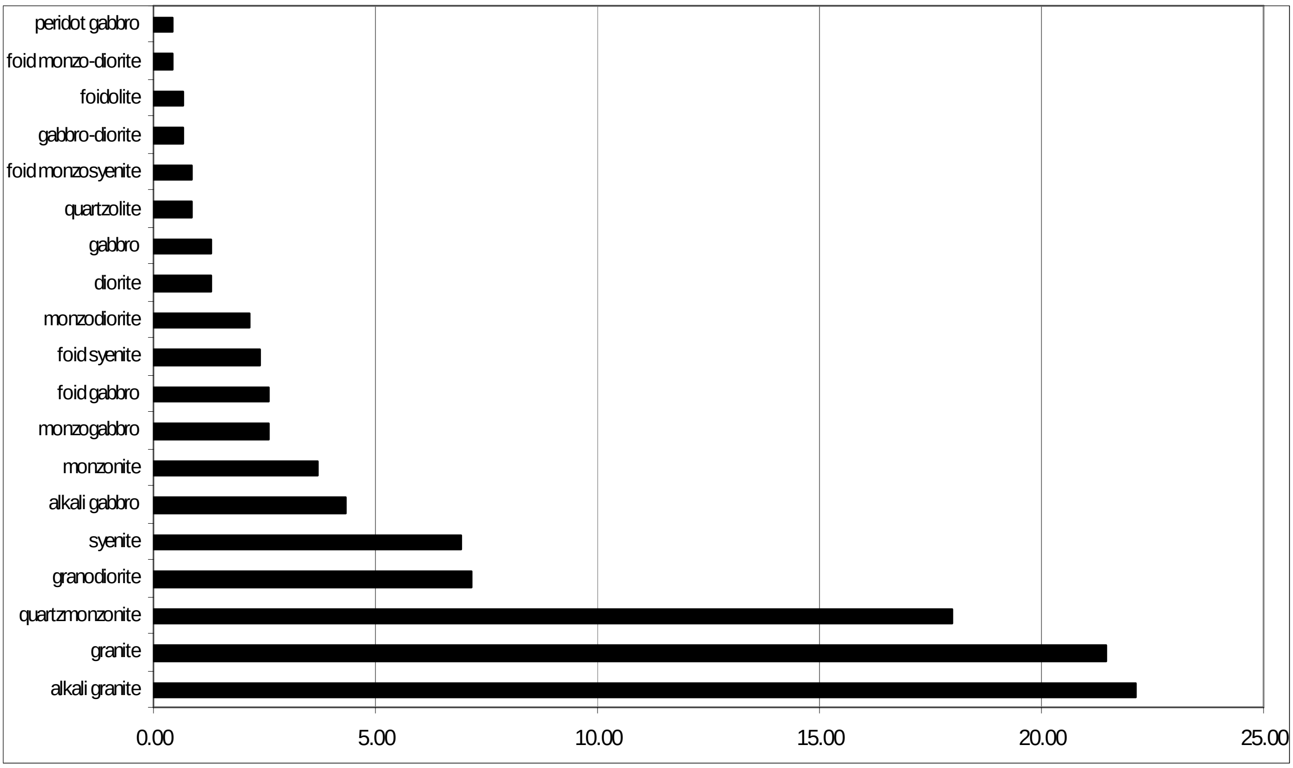
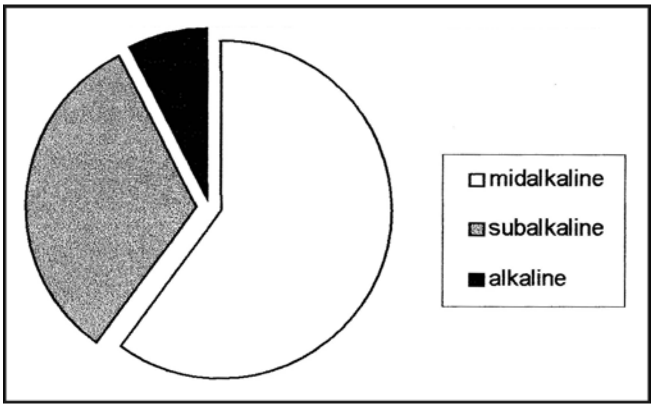



***Fig 9.1 Distribution of rock types and comparative composition of rock alkalinity in the Greater Lufilian Arc granitoid project. Based on the names of the modified TAS diagram of Middlemost, 1994a.***
*Note the absolute domination of alkali granite, granite and quartzmonzonite. Together these rock types account for almost 62% of all samples studied. That is also clear on Fig. 9.2.*



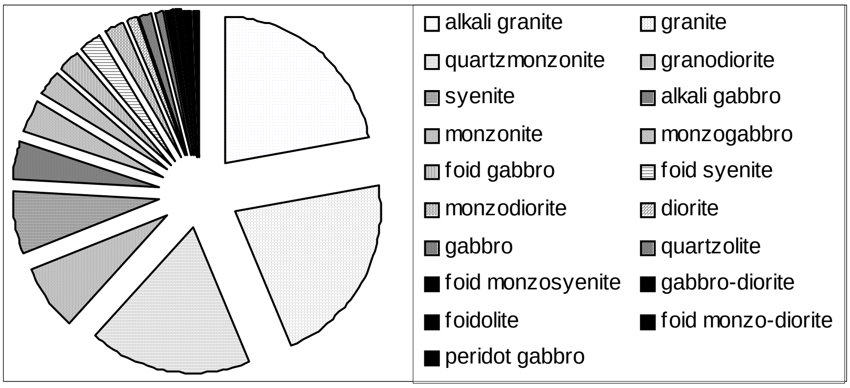




***Fig 9.2 Composition of the samples collected in the Greater Lufilian Arc.*** *The upper pie diagram* ***groups rocks according to*** *their alkalinity, sensu Middlemost, 1994. The lower diagram breaks the samples into their respective rock types.*

Midalkaline rocks predominate, whatever the point of view. That corresponds with the continental extension, anorogenic environment that has ruled formation of plutonic rocks in the Greater Lufilian Arc.

The average rock type distribution for the entire Greater Lufilian Arc closely resembles that of the Hook Granite Batholith, as indicated on Table 9.3.

### *9.3.1 Mafic, Ultramafic and Alkaline Rocks*

Mafic, ultramafic, carbonatitic and alkaline intrusions are well represented, albeit volumetrically minor, in most domains of the Greater Lufilian Arc that were studied. In certain cases, these rocks might be implicated in mineralizing processes (Kalengwa deposit, Lofdal rare earth mineralization and Lofdal carbonatites). These rocks occur in anorogenic epeirogenic uplift and rift-related environments. Mafic rocks are under-represented in the geochemical database, because they were not the primary sampling target.

The widespread small gabbroic bodies in the Greater Lufilian Arc were emplaced as mafic plugs in large, within-plate areas that were being subject to incipient rifting. The mafic plugs could intersect the sedimentary cover of the plate, including marine and continental deposits. A modern day analogue of the same process takes place in the environs of Filiya, Nigeria.

### *9.3.2 Rock Associations in Anorogenic Environments*

A frequent field observation is the persistent clustering of small bodies of red-altered granitoids, gabbroids, massive magnetite-hematite and quartz pods that are linked to ages around 550 and 750 Ma. The four-rock association seems to be a characteristic of continental extension anorogenic environments. It is spatially related to iron oxide-copper-gold mineralization.

A recurrent feature observed in most outcrops of the study area is the presence of two or more contrasting types of plutonic rocks. In some cases gabbroids and granitoids; in others, syenitoids and granitoids; even three or four types of granites and alkali granites. Many of the small areas also contain mafic, ultramafic and alkaline plugs and dikes of varying composition, such as lamprophyres, carbonatite and nepheline syenite.

The multiplicity of rock types in a small area seems to be another characteristic of continental extension anorogenic environments.

#### *9.3.3 Quartz Pods*

Quartz pods have been identified throughout most of the Greater Lufilian Arc region. They differ from veins, boudinaged veins and pegmatitic quartz units, particularly in geometry: outcrops of undeformed bodies are typically round to elliptical, and vary from a few to several-hundred meters in diameter. Dimensions of some quartz pods exceed four kilometers in diameter and there is geophysical evidence of even larger ones. They seem to be a special type of silicification. Hyper-alkaline, hydrothermal solutions seem to be involved in the transportation of silica and emplacement of the quartz pods. Quartz pods are emerging as a type of alteration that is associated to IOCG systems in the Greater Lufilian Arc. Improved identification in the field and an increased understanding of their physico-chemical features may aid in the exploration of mineral deposits.

#### *9.3.4 Iron Oxide Bodies*

Masive bodies of magnetite and/or hematite at macroscopic, mesoscopic and microscopic scales emplaced themselves by gradual replacement of the host rock. The process seems to involve silicate dissolution by hyper-alkaline hydrothermally-driven solutions.

#### *9.3.5 Round-Pebble Hydrothermal Breccias*

Round-pebble hydrothermal breccias occur often in and around IOCG systems throughout the Greater Lufilian Arc. They seem to have been produced by hyper-alkaline solutions that corroded previously angular hydrothermal breccias. In some cases, they act as good hosts for sulfide mineralization.

### 9.4 Ring Complex Clusters

Clusters of anorogenic granitoid ring complexes have been produced all along from Archean times to the present. Clustering of multiple anorogenic ring complex intrusions can form batholithic size bodies.

At least ten clusters of ring complexes were identified in the Greater Lufilian Arc. Ring complex clusters have the following characteristics: 1) Multiple ring complexes of varying chemical composition and size that might intersect each other. 2) Volcanic and plutonic rocks of roughly the same composition occur together. 3) Successive magmatic events of varying composition allowed for abundant opportunities of magma mixing and recycling of crustal materials. 4) The plan view geometry of un-tectonized ring complex clusters is roughly that of an isosceles triangle. 5) Less voluminous precursor and waning events of magmatism may occur. 6) The principal chemical composition of the magmas is midalkaline, but may ocassionally vary to alkaline and subalkaline. In extreme cases, it may be peralkaline and can even produce carbonatitic rocks. 7) Isolated bodies of mafic and ultramafic rocks often come in the latter stages of the process. 8) Total duration of ring complex cluster cycles averages 110 Ma.

Several cycles of ring complex clusters have repeatedly occurred in roughly the same location in at least three different localities. These repeated cycles were separated 1095 Ma in NW Zambia; 933 Ma at the Khorixas area, Namibia; and 50 Ma in West Lusaka, Zambia.

### 9.5 Tectonic Environment of Emplacement

The tectonic environment of emplacement for part of the rocks collected is not yet well constrained; active research is currently being carried out to address this issue. Nevertheless, several clear patterns are emerging: 1) The largest portion of granitoids collected are midalkaline rocks that formed in an anorogenic continental epeirogenic uplift environment. 2) Next come those formed in rift environments. 3) Another significant group of rocks formed in a post orogenic granitization environment. 4) Continent-continent collision environments were not positively identified. 5) Subductional magmatism seems to have been very restricted both in terms of time and areal extension. There is evidence of minor such magmatism in Paleoproterozoic rocks of Kalene Hill and in portions of the Kamanjab Batholith. In any given area, two or more of these settings may be superimposed. Anorogenic continental extension is the main geological process of the Arc.

Complete Wilson cycles were not identified in the domains of the Greater Lufilian Arc that were studied. The dominant magmatic process, as evidenced by the volume of extruded rock, is anorogenic continental epeirogenic uplift, closely-followed in time by a rift-related granitoid emplacement. Coalescing and overprinting aulacogens seem to be the main type of geological event in the arc.

The environment of emplacement of Paleoproterozoic rocks that occur throughout the Arc cannot be identified using the established methods for granitoid environment of emplacement. Intense sodic alteration and hematitization were observed in part of these rocks. Another alteration process is a net enrichment in potassium that is evident by the abundant biotite and alkali feldspar overgrowth. Part of the rocks showed diffuse crystal margins and abundant blue quartz phenocrystals. Incipient migmatitization of these rocks may have modified their chemistry to a point where they don't fit traditional procedures to evaluate granitoid environment of emplacement. The alteration processes just mentioned seem to have taken place before ~880 Ma, because the environment of emplacement of younger rocks can be identified.

## 9.6 High Thorium

High values of thorium were found in part of the granitoids of NW Zambia, Kafue Flats, Hook Granite Batholith (Zambia), Oas farm and Otjiwarongo environs (Namibia). They are high-heat producing rocks. The anomalous thorium content in some granitoids of the Greater Lufilian Arc induced and maintained long-lived, large convective cells of hydrothermal fluid flow.

High-thorium granitoids in all five domains have a particular trace element chemical signature that is not common, and probably were subjected to analogous geological processes at different points in time.

## 9.7 Correlation of Granitoids

Granitoid rock suites with closely matching chemistry and macroscopic features have been found to form in the same region, two or three times with up to a thousand million years of age difference. Source rocks and environment of emplacement for the anorogenic intrusive events were the same: for that reason, magmatic products turned out equivalent. These features preclude lithological or detailed geochemical correlation.

Rocks from the suites of Muliashi Porphyry and Mufulira, Zambia are an example of this. They both have pink and gray granitoids with similar compositions, but the ages of the rocks are completely different.

Several lithological correlations have been developed for granitoids in various domains of the Greater Lufilian Arc. The rocks cannot be properly correlated until more geochronological information is available.

## 9.8 Main Findings in Specific Domains

### *9.8.1 Hook Granite Batholith, Zambia*

Information currently available on geophysics, geochronology, rock distribution and geochemistry from the Hook Granite Batholith fit quite well with an intracontinental, anorogenic, ring complex cluster origin. The batholith is mainly composed by midalkaline granitoids. Alkali granites, quartzmonzonites and granites make up 70% of all rocks.

### *9.8.2 Nchanga Granite, Zambia*

The Nchanga Granite has all the characteristics of an anorogenic granite ring complex. Chemistry of its rocks crosses the midalkaline to subalkaline fields. Parts of the pluton are made of high heat producing granites that maintained a long-lived circulation of hydrothermal fluids. The Nchanga Granite might have contributed to the origin of copper in its environs.

### *9.8.3 Kamanjab Batholith, Namibia*

Sixteen suites with more than two contrasting rock types were identified in the Kamanjab Batholith. No two suites are identical, and they are made by a large variety of rock types. This multiplicity of rock types at a given site is one of the characteristics of anorogenic environments in the Greater Lufilian Arc.

There is no direct proof of the presence of ring complexes at the Kamanjab Batholith. Nevertheless, several sources of evidence point to the batholith as a cluster of ring complexes. Among others, these are: 1) the lack of continuity in the rock types along traverses; 2) the presence of multiple rocks types in at least fifteen discrete sites; 3) General anorogenic character of most of the rocks; 4) three quarters of the rocks in the suite are midalkaline; 4) the size and shape of the batholith, as well as its event diagram has similarities with other ring complex clusters.

#### *9.8.5 New Temporal Constrain to Katangan Sedimentation*

Granitic dikes emplaced at the Nchanga mine area in anorogenic extensional environments were dated at ~765 Ma. They provide the youngest age of deposition for that portion of the Katanga sedimentary sequence at Nchanga (Roan sediments), and might provide a significant bracket age for mineralization.

#### *9.8.6 Khorixas Inlier-Kamanjab Batholith*

Geological history for the Khorixas Inlier and the Kamanjab Batholith are significantly different. They probably were not in the same geographic position all the time. Older basement is known in the Khorixas Inlier than at the Kamajab. The two regions seem to have had a common geological history for the past 550 Ma.

#### *9.8.7 Long-Lived Fractures*

E-W-trending regional fracture systems that run parallel to the elongation of the Greater Lufilian Arc play an important role in the emplacement of magmatism and IOCG mineralization. They acted as routes for intrusion, channels for fluids and control for ore deposition. Those structures are generally parallel to the main Lufilian Arc trend, and could have been normal syn-rift faults that have been reactivated throughout geological history. Some N-S-trending structures are also mineralized and they are sub-perpendicular to the main trend of the Lufilian Arc.

### 9.9 Metallogeny

Various types of mineralization were seen to be associated with intrusive rocks along the Greater Lufilian Arc (Table 9.4). These include rare earth mineralization associated to alkaline dikes and carbonatites in the Khorixas Inlier, sedimentary-hosted gold (so-called “Carlin”-style deposits), several low-sulfidation hydrothermal gold occurrences, low sulfidation hydrothermal copper depostis, epigenetic copper vein deposits, alkaline porphyry molybdenum (-copper?) style mineralization, sedimentary-hosted copper-cobalt deposits, and a wide variety of iron oxide-copper-gold and related deposits and prospects. Several Paleoproterozoic rocks throughout the Greater Lufilian Arc are enriched in copper. Some Mesoproterozoic syenites and alkali granites are enriched in zinc. The significance of the latter observation remains unclear. Paleoproterozoic copper-rich rocks could be the source of metal for later events. Incipient migmatitization of those rocks could have remobilized the copper. Copper is probably being recycled. Very little skarn mineralization was observed in Katangan carbonates, even though they are intruded by multiple plutonic episodes. Possible exceptions occur around the Hook batholith. The Samba deposit is not considered to be a copper porphyry; it is a low sulfidation epithermal copper mineralization hosted in pyroclastic rocks that were sheared during regional metamorphism.

#### *9.9.1 Metallogenic Epochs*

At least eight discrete periods of mineralization can be interpreted from Table 9.4 (The same are simplified on Table 9.5). Where possible, radiometric ages have been used to place the various events. Most have been assigned to specific ages by correlation or association. Six deposits could not be placed chronologically and are included at the bottom of the list. There is a wide-spread series of mid-alkaline intrusions emplaced around 750 Ma that produces a variety of mineral deposits. Another such event (separated in at least three different phases: 500-513, 550 and 583 Ma) took place around 540±40 Ma. Five less well defined events took place as indicated on Table 9.5. From old to young, they occurred at ~1970, ~1930, ~1866, 1097-1059 and ~460 Ma (See Tables 9.4 and 9.5). The dominant deposit type is iron oxide-copper-gold mineralization.

The age of sedimentary-hosted copper mineralization in the Copperbelt is currently being re-evaluated using Re-Os dating at the University of Arizona. Three tentative ages for them are 796-756, ~583 and ~550 Ma.

The main events of sedimentary-hosted gold mineralization in Namibia are ~750 Ma in the environs of Sesfontein, ~550 Ma in Eastern Namibia. The age of the Zambian deposits and prospects could not be estimated.

At least two distinct events of disseminated copper mineralization associated to midakaline granitoid intrusives were identified in the Kamanjab Batholith. The first took place around 1975 Ma and the second around 1928 Ma.

# *Table 9.4 Main Metallogenic Events Observed - Greater Lufilian Arc*

| Commodities | Mine, Deposit, Prospect, Event | Deposit Type | Age | @ | Tectonic Environment |
|---|---|---|---|---|---|
| Au | Sasare,Zm | IOCG | 460 | | anorogenic continental rift+ |
| Au,Cu,(Pb?) | Navachab Mine, Nm | structurally-controlled carbonate replacement | ~490 | E | ? |
| Cu,Au | Kansanshi Mine,Zm | ? | 500-513 | E | extension |
| Cu,Co,Au,U | Shituru Mine, D.R.Congo | IOCG | 500-513# | E | extension |
| Cu,Co,Ni | Luiswishi Mine, D.R.Congo | IOCG | 500-513# | E | extension |
| Cu,Co,Ni,Au,U,etc. | Kamoya Mine, D.R.Congo | IOCG | 500-513# | E | extension |
| Mo | Marinkas Kwela Deposit, Nm | Mo porphyry | 520-560 | E | anorogenic continental rift |
| Cu,Au,Mn,LREE | Kitumba deposit,Zm | IOCG | 533 | E | anorogenic continental rift |
| Cu,Au,Mn,LREE | Kantonga deposit, Zm | IOCG | 533 | E | anorogenic continental rift |
| Cu,Ag,Au,Fe | Hook Satellites, Zm | IOCG | 533 | E | anorogenic continental rift+ |
| Au,<Cu | Dunrobin Mine, Zm | Au-rich IOCG | 533 | E | anorogenic continental rift+ |
| Py,Cu,Au | Nampundwe Mine, Zm | IOCG | 538(L-207) | E | anorogenic continental rift+ |
| Cu,Au,As,Pb,Zn | Hippo Mine, Zm | IOCG | 538 | E | anorogenic continental rift+ |
| Au | Otavi Mts., Nm | Sed-hosted Au | ~550 | E | anorogenic continental rift |
| Au | Otjiwarongo, Nm | Sed-hosted Au | ~550 | E | anorogenic continental rift |
| Cu,Au | Kombat Mine, Nm | IOCG | ~550* | E | anorogenic continental rift |
| Au | Otjikoto Mine, Nm | IOCG | ~550* | E | anorogenic continental rift |
| Cu,Au | Kafue Flats, Zm | IOCG | 550(L-211) | E | anorogenic continental rift |
| Au | Kamanjab, Nm | Au epithermal | 570-677 | E | ? |
| Zn,Pb | Kabwe Mine, Zm | ? | ? | E | ? |
| - | Verangian Glaciation | - | 580 | E | - |
| Cu,Co | CuBelt minzn, Nchanga Mine, Zm | Sedimentary-hosted Cu | 583 | E | - |
| Cu,Co | CuBelt minzn, Mufulira Mine, Zm | Sedimentary-hosted Cu | 583 | E | anorogenic continental rift+ |
| Cu,Co | CuBelt minzn, Musoshi Mine, Zm | Sedimentary-hosted Cu | 583 | E | |
| Cu,Co | CuBelt minzn, Chambishi Mine, Zm | Sedimentary-hosted Cu | 583 | E | |
| - | Marinoan Glaciation | - | 630 | | - |
| - | Sturtian Glaciation | - | 710 | | - |
| Cu,Ag,LREE,U,Au? | Kalengwa Mine, Zm | IOCG | 745 | I | anorogenic continental rift+ |
| Cu,Au,LREE | Kasempa Area, Zm | IOCG | 750 | I | anorogenic continental rift+ |
| Cu,Au? | Kametete deposit, Zm | IOCG | 750 | I | anorogenic continental rift+ |
| Au | Sesfontein, Nm | Sed-hosted Au | 745-756 | I | anorogenic continental rift |
| Cu,Nb,REE,Au? | Kesya carbonatite, Zm | IOCG | 745-756? | I | anorogenic continental rift+ |
| Cu,Co | Copper Valley prospects + mine, Nm | IOCG | 745-756 | I | anorogenic continental rift+ |
| REE,Zn,Cu?,Au? | Oas farm prospects, Nm | IOCG | 745-756 | I | anorogenic continental rift+ |
| REE,Cu?,Au? | Lofdal farm prospects, Nm | IOCG | 745-756 | I | anorogenic continental rift+ |
| Cu,Co,Ni | Luamata deposit, Zm | IOCG | 745-756 | I | anorogenic continental rift+ |
| Cu,Co | Copperbelt initial Cu minzn, Zm | Sedimentary-hosted Cu | 756-796 | I | anorogenic continental rift |
| Cu | Omitiomire deposit, Zm | Sedimentary-hosted Cu | L or younger | | anorogenic continental rift |
| Au,Cu | Kamachopolo, SW Kasempa, Zm | Low sulfid. epithermal | L or younger | | anorogenic continental rift |
| Au | Lunga, Zm | Low sulfid. epithermal | L or younger | | anorogenic continental rift |
| Cu | Mkushi mines and prospects, Zm | Intrusion-related minzn | 1059 | L | extension |
| Cu,Au | Witvlei deposit, Nm | IOCG | 1097(L-638) | L | anorogenic continental rift+ |
| Cu,Au?,Ag? | Mnzd area 3 Kamanjab Batholith, Nm | Disseminated Cu | 1866(L-993) | | |
| Cu,Cu,LREE | Mwinilunga, W Zm | IOCG? | 1928(L-030) | U | |
| Cu,Cu,LREE | Kamdescha f., Kamanjab Batholith,Nm | IOCG, Au, Cu | 1937(L-868) | U | |
| Cu,Cu,LREE | Tevrede f., Kamanjab Bathlith,Nm | IOCG | 1937(L-855) | U | |
| Cu,Mo | Samba Cu prospect, Zm | schist-hosted Cu | 1965 | V | ? |
| Cu,Au?,Ag? | Mnzd area 2, Kamanjab Batholith,Nm | Disseminated Cu | 1876(L-969) | | |
| Co,Ni,Cu | Kalumbila deposit, Zm | Sedimentary-hosted Cu derived from an IOCG | * | I | hydrothermal rift-related brines,can be I,L or even older up to 1800Ma. |
| Cu | Lumpuna prospect, SW Luanshya,Zm | Cu porphyry | ? | | Subduction |
| Cu | Chifumpa, 80km SE Kasempa, Zm | Cu porphyry | ? | | Subduction |
| Au,<Cu | Karibarembi, 49km S Kalenwa, Zm | Sed-hosted Au | ? | | |
| Au,<Cu | Kililamirombwe, 124km SSE Kasempa,Zm | Sed-hosted Au | ? | | |
| Cu | Dongwe, Zm | High+low sulf. epitherm | ? | | Subduction |

+Tectonic environment of emplacement was inferred from geochemistry. *The age is based on a nearby similar age. #Estimated age.
@Magmatic event in geochronological correlation diagrams (Figs A79 to A83).
The age of the six last items of the table is uncertain.

### *Table 9.5*
## Simplified Classification of Metallogenic Events in the Greater Lufilian Arc

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| Commodities | Location | Deposit Type | Age | * | Environment |
|---|---|---|---|---|---|
| Au | Sasare, Zm | IOCG | 460 | | ACR |
| Cu,Co,Ni, Au,U,Fe | Kansanshi, Zm + some southern Congolese Fe + Cu-Co deposits | IOCG + Kansanshi veins | 500-513 | Eo | Extension |
| Mo | Marinkas Kwela | Mo porphyry | 520-560 | E | ACR |
| Cu,Au,Fe, REE,Ag,Zn,Pb | Hook Granite batholith satellite bodies, Zm | IOCG | ~533 | E1 | ACR |
| Cu,Au | Otjiwarongo, Otavi Mts., Nm; Kafue Flats, Zm | IOCG + Sedimentary-hosted Au + Navachab,Nm | ~550 | E2 | ACR |
| Cu,Co (U) | Copperbelt and Congolese Cu-Co mineralization hosted in sediments; remobilization and mineralization | Sed-hosted Cu (epigenetic overprint) | ~583 | E3 | Event related to Verangian Glaciation? |
| Cu,Co,Ni,Au | Kabompo Dome, Zm | IOCG, sed-hosted Co-Ni-Cu | ~730 | I | CEUG |
| Cu,Au,REE, Ag,Mn | Kalengwa-Kasempa area,Zm Oas, Lofdal, Mesopotamie, Nm | IOCG | ~745-756 | I | ACR |
| Cu,Co | Initial copper mineralization in the Zambian Copperbelt (and Katanga?) | Sed-hosted Cu | 756-796 | I-J | ACR |
| Cu,Au | Witvlei, Nm; Mkushi,Zm; Omitiomire,Zm | IOCG + Intrusive related mineralization | 1059-1097 | L | ACR |
| Au,As,Bi,Sb | Karibarembi and Kililamirombwe, Zm | Sed-hosted Au | L or younger | L | ACR |
| Cu,Au? | Kamanjab Batholith, Nm | IOCG, hydrothermal Cu dissemination | 1866 | U | environment cannot be identified - probably CEUG |
| Cu,Au? | Kabompo Dome, Mwinilunga, Lumwana, Zm | Schist-hosted Cu | 1928 | U | ? |
| Cu, Au,Fe,F,REE | Kamanjab Batholith, Nm; Mwinilunga, Zm (?) | IOCG | 1930 | U | ACR |
| Cu,Mo | Samba, Zm | Schist-hosted Cu | 1965 | V | ? |
| Cu,Au,Ag? | Kamanjab Batholith, Nm | Hydrothermal Cu dissemination | 1975 | V | CEUG |

NOTE: ACR = Anorogenic continental rift. CEUG = continental epeirogenic uplift granitization.
* Letters in the fifth column refer to labels for magmatic events in geochronological correlation diagrams (Figs A79 to A83). White and gray coloration serves to separate major metallogenic times.

### *9.9.2 Iron Oxide-Copper-Gold Mineralization*

The iron oxide copper-gold (IOCG) style of mineralization is far broader in terms of both spatial distribution and age of emplacement than previously thought. IOCG deposits have been identified in both Namibia and Zambia. In Namibia, for example, the IOCG deposit Tevrede is currently being explored by junior mining corporations in the northwestern portion of the Kamanjab batholith; in addition, the Kombat copper mine in the Otavi Mountains and Otjikoto, a gold deposit in the environs of Otjiwarongo, seem to be IOCG deposits. Several IOCG-like mineralized areas were identified at the Oas, Lofdal, Mesopotamie and Gelbingen farms as outliers to the Kamanjab Batholith. Zambia also has several known IOCG deposits like the Kalengwa copper-silver mine, the Kitumba and Kantonga copper deposits and others around the Kasempa area. The Nampundwe pyrite mine as well as Dunrobin gold mine also have IOCG characteristics.

Quartzites are good hosts for mineralization. This was observed in several Namibian areas, including the southern part of the Oas farm, the Gelbingen farm and the western portion of the Kamdescha farm, bordering the Kamanjab Batholith. Quartzites fracture in a brittle manner that is ideal for hydrothermal brecciation. Equivalent rocks might host mineralization in Zambia.

The main IOCG events that have been identified in the Greater Lufilian Arc took place during eight time periods. These are listed on Table 9.6. The possible IOCG events that took place in the basement to the Zambian Copperbelt (at Chambishi, Mufulira, the main Copperbelt, Konkola and Nchanga) are not very well defined or constrained geochronologically.

***Table 9.6 Periods of iron oxide-copper-gold mineralization in the Greater Lufilian Arc.***

| Period | Main representative mineralization |
|---|---|
| ~460 Ma | Sasare, Zambia |
| ~533 Ma | Hook Granite Batholith satellites, Zambia |
| ~550 Ma | Otjiwarongo, Namibia; Kafue Flats, Zambia |
| ~746 Ma | Kalengwa-Kasempa, Zambia; Khorixas, Namibia |
| ~825 Ma | Copperbelt, Zambia (possible, see section 6.4) |
| ~1078 Ma | Witvlei, Omitiomire, Namibia |
| ~1937 Ma | Kamanjab Batholith, Namibia |

The rocks of many IOCG deposits and prospects in the Greater Lufilian Arc are pristine. There is no significant deformaton involved. Hydrothermal brecciation and other mineralization features are un-deformed. This may be very useful to study mineralization and alteration processes.

### *9.9.3 Association of Sedimentary Hosted Copper Mineralization with IOCG Mineralization*

A significant finding is the juxtaposition of iron-oxide-copper-gold mineralization underneath the sedimentary-hosted copper deposit at Witvlei, Namibia. This metallogenic event occurred at 1110 Ma. Secondary copper in the sedimentary-hosted deposit might have come from the IOCG deposit that lies underneath. This idea may generate a new concept for the origin of the Copperbelt-Katanga copper and cobalt deposits. The concept also opens an entire new age gap for the exploration of base metal mineralization in the Greater Lufilian Arc and the surrounding environment, including South Africa. There is additional evidence of IOCG mineralization related to sediment-hosted copper in other parts of Namibia and Zambia, including the Chambishi area and parts of the basement to the Copperbelt.

At least three discrete time periods show IOCG mineralization in close temporal spatial association with sedimentary-hosted copper deposits. The first took place around Witvlei from 1108 to 1059 Ma. The second and third ocurred in the basement to the Zambian Copperbelt from 882 to 725 Ma and from 607 to 500 Ma.