PRELIMINARY EVIDENCE FOR A SECOND ~525-545 Ma OLD EVENT OF GRANULITE FACIES METAMORPHISM IN THE MOZAMBIQUE BELT OF TANZANIA AND ITS IMPLICATIONS FOR A TWO-STAGE MODEL FOR GONDWANA ASSEMBLY

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ABSTRACT

Garnets from two samples of the Kitumbi granulites in the Mozambique Belt of north eastern Tanzania yield Sm-Nd ages of 525±15 Ma and 545±15 Ma. At the 95% confidence level, these ages are younger than the 576 ±15 to 634±16 Ma (Mean 606±12 Ma) ages previously reported from the more extensive Eastern Granulites. The Kitumbi garnets are therefore interpreted as dating cooling from a granulite facies event that is distinctly younger than the 630-700 Ma event that produced the Eastern Granulites. Unlike the Eastern Granulites, the Kitumbi rocks occur as small enclaves not separated from the surrounding amphibolite facies gneisses by any obvious structural discontinuity, lack the continental margin geochemical signatures that characterise the Eastern Granulites and yield late Archean depleted mantle crustal formation ages, similar to those obtained from the surrounding gneisses. These characteristics suggest that, unlike the Eastern Granulites that are isotopically exotic slices emplaced onto the surrounding amphibolite facies gneisses, the Kitumbi granulites are products of ~550 Ma old in situ granulite facies metamorphism of the surrounding country rocks. The existence of a regional granulite facies event at ~530-550 Ma offers a way of reconciling the palaeomagnetic and petrological/geochronological evidence for Gondwana assembly. Thus, as has been previously proposed by Meert et al. *(1995), the 630-700 Ma old event that produced the Eastern Granulites may record regional crustal thickening arising out of collision of India, Madagascar, parts of Easten Antarctica and the Kalahari craton (IMSLEK terranes) with the Congo craton and the Arabian Nubian Shield (ANS). The younger granulite event recorded in the Kitumbi area could then mark a younger collision between Australo-Antarctica and the combined IMSLEK-Congo-ANS collage marking the final assembly of Gondwana.*

INTRODUCTION

The Mozambique Belt (MB) of eastern Africa is considered to be one of the main sutures along which the Neoproterozoic assembly of Gondwana took place (Burke *et al.* 1977, McWilliams 1981, Shackleton 1996). For this reason, various workers have attempted to establish its age in order to put constraints on the time of Gondwana assembly. In particular, a lot of effort has been directed at attempting to date the metamorphic age of the numerous granulite facies complexes which form an important lithological component within the belt (Coolen *et al.* 1982, Maboko *et al.* 1985, Muhongo & Lenoir 1994, Maboko 1995). The attention cast on the age of granulite facies metamorphism arises from the fact that regional granulite facies terranes are believed to form in thickened crustal segments most commonly along zones of continent-continent collision (Newton & Perkins 1982, Harley 1992). Thus, in the context of the MB, granulite facies metamorphism has been associated with the collision of West and East Gondwana or fragments thereof during the final stages of assembly of the Neoproterozoic supercontinent. Whereas the age of peak granulite facies metamorphism in the MB has been dated at between 630 and 700 Ma (Coolen *et al.* 1982, Maboko *et al.* 1985, Muhongo & Lenoir 1994, Maboko 1995, 2000a), suggestive of final collision in this time interval, palaeomagnetic evidence (McWilliams 1981, Meert & Van der Voo1997, Meert *et al.* 1995) support a much younger age of collision at ~550 Ma. The palaeomagnetic data, combined with the few ~550 Ma ages that have been reported in various parts of the MB, have been used by Meert *et al.* (1995) and Meert and Van der Voo (1997) to propose a two stage assembly model for East and West Gondwana. According to these authors, the first collision amalgamated India, Madagascar and Sri Lanka (IMSLEK) with East Africa along the Mozambique Belt between 650 and 800 Ma in what Stern (1994) has termed the East African Orogen. The second collision occurred between the combined IMSLEK-East Africa collage and Australo-Antarctica during what Meert *et al.* (1995) called the Kuunga Orogeny. Although ~550 Ma granulites are known from southern India (Kroner 1993), southern Madagascar (Windley *et al.* 1994, Kroner *et al.* 1996), Sri Lanka (Shiriashi *et al.* 1994, Unnikrishnan-Warrier *et al.* 1995), Mozambique (Jamal *et al.* 1999) and parts of East Antarctica (Shiriashi *et al.* 1994.), within East Africa, there has been so far little evidence of a post ~630 Ma granulite facies event, (apart from the ~545 Ma old granulites reported by Ayalew and Gichile (1990) in southern Ethiopia) which could be linked to the Kuunga orogeny of Meert *et al.* (1995). In this paper, preliminary Sm-Nd garnet ages of between 525 and 545 Ma from the Kitumbi area in north eastern Tanzania are presented. The data suggest presence of a possible Kuungan granulite facies event in the Mozambique Belt of East Africa.

Geological Background

The Mozambique Belt of eastern Africa contains extensive tracts of granulite facies metamorphic rocks. In the eastern part of the Tanzanian sector of the MB most of the granulites occur in a N-S trending, semi-continuos belt, some 900 km long, for which Hepworth (1972) coined the term Eastern Granulites (Fig. 1). The Eastern Granulites show remarkably similar structural and petrological characteristics with PT conditions estimated at 9.5 – 11 kb and 840±40 °C (Coolen 1980, Maboko 1997, Appel *et al.* 1998). On the basis of whole rock Sm-Nd systematics, Maboko (1995), Maboko (2000b, c) and Moller *et al.* (1998) showed that the protolith for most of the Eastern Granulites was juvenile material extracted from the mantle during the Neoproterozoic (900 – 700 Ma).

Hepworth (1972) describes other granulite occurrences in the western and central parts of the MB. The Western Granulites occur as small enclaves within amphibolite facies granitic gneisses near the Archean-Proterozoic boundary in central Tanzania. Like the surrounding gneisses, they show late Archean crustal formation ages (Ben Othman *et al.* 1984). Their metamorphic age has, however, not been established although the oldest biotite Rb-Sr ages from the area are ~630 Ma, suggesting that the granulite facies metamorphism must be older than this (Maboko 2000b). The Central Granulites constitute the occurrences west of the Eastern Granulites but east of the Western Granulites in the Ukaguru area for which no published petrological and isotopic work exist.

The Kitumbi Granulites occur as small enclaves within amphibolite facies granitic gneisses in the lowlands between the Usambara and Wami River complexes of the Eastern Granulites (Fig. 1).

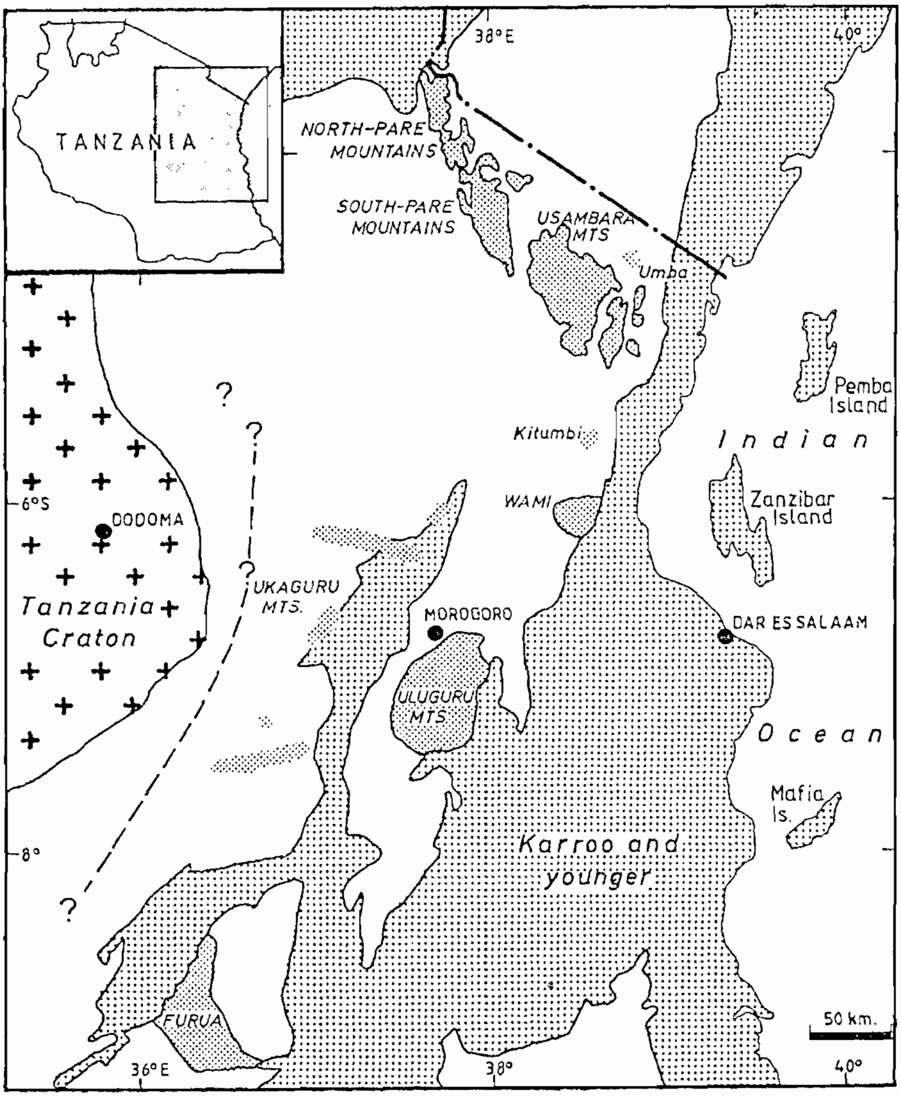

Fig. 1: Sketch geological map of eastern Tanzania showing the Kitumbi area. The other major occurences of granulites in the Mozambique Belt (Pare, Usambara, Wami, Uluguru and Ukaguru) are shaded. The dotted line marks the inferred boundary between the Palaeoproterozoic Usagaran Belt and Neoproterozoic Mozambique Belt (After Appel *et al.* 1998)

Petrographically, the Kitumbi granulites consist of quartz, plagioclase, clinopyroxene, orthopyroxene and garnet with or without hornblende and biotite. Garnet ($alm_{0.55-0.56}\ grs_{0.17}sp_{0.02-0.03}$) occurs in clusters of small equant grains, sometimes in textural equilibrium with clinopyroxene but not with orthopyroxene. Orthopyroxene occurs as very rare, mostly relict grains, which have been heavily altered to a brown fluff of Fe-oxides. Clinopyroxene forms small pale green isolated grains with locally developed small retrograde rims of hornblende. The petrographic characteristics suggest that subsequent to the granulite facies metamorphism, the rocks were strongly overprinted by a retrograde event during which the pyroxenes were hydrated to form hornblende and the brown fluff of Fe-oxide. Most of the hornblende and biotite, however, appear to have been part of the granulite facies assemblage. The small size of the garnet, their occurrence in isolated clusters and the fact that they are never in contact with orthopyroxene suggest that they developed relatively late as the granulites were cooling at near isobaric pressure.

MATERIALS AND METHODS

Two samples from the Kapico quarry in Kitumbi, were analysed for major and trace elements at the Pheasant Memorial Laboratory (PML) for Geochemistry and Cosmochemistry of the Institute for the Study of the Earth's Interior at Misasa, Japan. The major element compositions together with Ni and Cr contents were analysed on fused disks using a Phillips PM2400 X-ray fluorescence spectrometer. The trace element analyses were performed on a YOKOGAWA PM@2000 ICP-MS using the flow injection method (Makishima & Nakamura 1997). The analytical reproducibility is better than 6.5% and typically ~2.5% for trace elements and better than 0.2% for the major elements.

The samples were also analysed for Nd isotopic composition as well as Nd and Sm concentrations using a Finnigan MAT262 mass spectrometer. Additionally, pure garnet separates were obtained from the rock samples using conventional heavy liquid and magnetic separation techniques and also analysed for Nd isotopic composition and Nd and Sm concentrations. The analytical procedure for chemical separation and mass spectrometry are described in Shibata *et al.* (1989) and are essentially similar to those described in Maboko and Nakamura (1996). The isotopic ratios were normalised to $^{146}Nd/^{144}Nd = 0.7219$. Replicate analyses of the La Jolla Nd standard gave $^{143}Nd/^{144}Nd = 0.511920 \pm 13$ (2σ n = 9). Maximum 2σ uncertainties in the Sm/Nd ratios derived from long term reproducibilities of standard samples are 2%. Typical blank values are 5 and 10 pg for Sm and Nd respectively and negligible. In addition, the chemical composition of the garnets was obtained using a Horiba EMAX-7000 energy dispersive X-ray spectrometer assembled onto a Hitachi S-3100H scanning electron microscope.

RESULTS AND DISCUSSION

The isotopic data, depleted mantle crustal formation ages, calculated whole rock-garnet ages and major and trace element compositions are shown in Tables 1 and 2. The samples have an enderbitic bulk composition and REE patterns characterised by relative depletion in the HREE (Fig.2). Depleted mantle crustal formation ages calculated using the parameters of Michard *et al.* (1985) are ~2680 and 2580 Ma for samples KAP1 and KAP2 respectively (Table 1). Corresponding garnet-whole rock ages are 545±15 and 525±13 Ma (errors are quoted at the 95% confidence level) for KAP1 and KAP2 respectively.

Table 1: Sm-Nd whole rock (WR) and garnet (Gt) data

Sample	Nd(ppm)	Sm(Ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	TDM (Ma)	Carnet age (Ma)
KAP1 WR	42.03	8.28	0.1186	0.511285	2680	-
KAP1 Gt	5.967	5.680	0.5730	0.5129-7	-	545±15
KAP2 WR	21.91	3.50	0.0960	0.510969	2580	-
KAP2 Gt	6.881	8.973	0.7849	0.523337	-	525±13

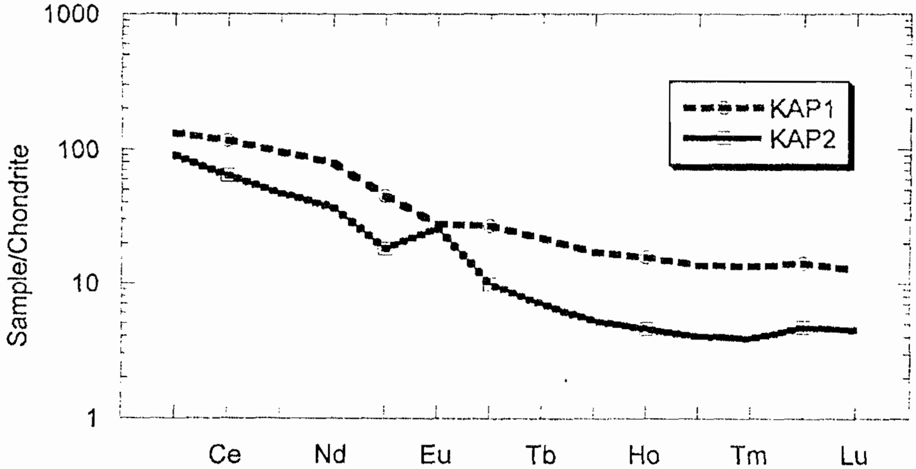

Fig. 2: Chondrite normalised REE patterns for two samples for the Kitumbi granulites Tanzania. Note the light (L) REE enriched patterns. The elements are from left to right La, Ce, Pr, Nd Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu

Table 2: Major (weight %) and trace element (PPM) compositions

	KAP1	KAP2
SiO2	56.7	57.3
TiO2	0.815	0.807
Al2O3	18.6	19.7
Fe2O3 tot	5.69	4.5
MnO	0.095	0.068
MgO	2.18	1.53
CaO	5.68	4.89
Na2O	5.32	5.41
K2O	1.7	2.45
P2O5	0.237	0.198
Ni	17.0	8.0
Cr	35.0	18.0
Rb	22.0	33.0
Sr	643.0	799.0
Y	33.0	9.3
Ba	653.0	1664.0
La	41.0	28.0
Ce	94.0	52.0
Pr	12.0	5.7
Nd	47.0	22.0
Sm	8.8	3.5
Eu	2.0	1.9
Gd	7.0	2.6
Tb	1.0	0.33
Dy	5.5	1.7
Ho	1.1	0.33
Er	2.9	0.85
Tm	0.43	0.13
Yb	2.9	0.99
Lu	0.41	0.14
Pb	14.0	14.0
Th	3.4	0.52
U	0.28	0.41

The Kitumbi granulites, like the Western Granulites near the boundary between the MB and the Tanzania craton, occur as small enclaves surrounded by amphibolite facies granitic gneisses. Their chemistry and manner of occurrence suggest a magmatic protolith with an enderbitic bulk composition. Both the Western Granulites and the Kitumbi Granulites yield late Archean Nd crustal formation ages that are quite distinct from the Neoproterozoic or mixed ages found in the Eastern Granulites (Maboko 1995, , Moller *et al.* 1998, Maboko 2000b, c). The isotopic difference with the Eastern Granulites is also mirrored in marked petrographic differences. Whereas the Eastern Granulites generally show minimal retrograde effects and are characterized by coarse grained garnets in equilibrium with unaltered coarse pyroxenes, the

Kitumbi pyroxenes have been heavily retrograded and the garnets show textural evidence of late growth. Other differences between the Kitumbi and the Eastern Granulites include their mode of occurrence. The latter occur as extensive complexes clearly separated by structural discontinuities from the surrounding amphibolite facies gneisses which generally show late Archean crustal formation ages (Maboko 1995, Moller *et al.* 1998, Maboko 2000b). The Kitumbi granulites, on the other hand, occur as small enclaves surrounded, without any obvious structural discontinuity, by gneisses that are also characterized by late Archean crustal formation ages. This mode of occurrence suggests that whereas the Eastern Granulites are fault-bound, isotopically exotic slices emplaced onto the surrounding gneisses, the Kitumbi granulites represent products of in situ prograde metamorphism of the surrounding rocks.

An interesting question arising out of this observation is whether the granulite metamorphism in the Kitumbi rocks is coeval with that recorded in the Eastern Granulites. An examination of the available isotopic data put the time of peak metamorphism in the Eastern Granulites at between 630 and 700 Ma (Maboko *et al.* 1985, Muhongo & Lenoir 1994, Maboko & Nakamura 1995, Moller *et al.* 1998, Maboko 2000a, c). Even if we restrict ourselves to published Sm-Nd ages, the range of ages found in the Eastern Granulites falls between ~576 and 630 Ma with a mean of 606±12 Ma (Table 3). At the 95% confidence interval, these ages are significantly older than the 525-545 Ma garnet ages found in the Kitumbi area. This suggests that the 525-545 Ma Kitumbi ages are unlikely to represent stages in the cooling history from the event that produced the Eastern Granulites. Rather, the ages are best interpreted as dating cooling from a distinctly younger granulite facies event in the MB. Given the ambiguity surrounding estimates of the closure temperature (T_C) of garnet to the Sm-Nd system (Wang *et al.* 1998), it is difficult to estimate how close these ages date the peak of the Kitumbi granulite facies metamorphism. Using the ~750°C closure temperature suggested by Vance and O'Nions (1990) and Coghlan (1990), the ages would closely date the peak of the event. If, however, the lower T_C estimates of ~500°C (Maboko & Nakamura 1995) to 600°C (Mezger *et al.* 1992) are used, there could be a considerable time lag, the length of which would depend on the cooling rate, between peak metamorphism and the closure of the garnets. Within the Eastern Granulites, a comparison of the oldest Sm-Nd garnet ages and the U-Pb data of Moller *et al.* (1994) suggests that the oldest garnet ages may date closely peak metamorphism (Maboko 2000c). If this is the case for the Kitumbi rocks as well, the 545±15 Ma age recorded by sample KAP1 may similarly be a close estimate of the age of peak metamorphism.

The 525-545 Ma ages of the Kitumbi garnets are similar to the ~530 Ma biotite Rb-Sr age reported by Maboko (2000b) from the Bubu Cataclasites along the boundary between the Tanzania craton and the MB. Maboko (2000b) interprets the biotite age as dating closely the Bubu deformation, an

\event considered as marking an episode of tectonic escape towards the end of Mozambiquean orogenic activity. Thus, if the garnet ages closely date the peak of granulite facies metamorphism in the Kitumbi area, the metamorphism was coeval with this event of tectonic escape. The Kitumbi ages are also similar to ~545 Ma zircon U-Pb ages reported by Ayalew and Gichile (1990) from the Bergudda granulites of southern Ethiopia. This suggests that the 525-545 Ma event recorded by the Kitumbi garnet may have regional significance. However, it is obvious that more data are required before the true regional significance of this episode in Tanzania can be established.

Table 3: Summary of published Sm-Nd garnet ages from the Eastern Granulites

Area	Age (Ma)	Reference
Uluguru	615-633	Maboko and Nakamura (1995)
Wami	580-618	Maboko (2000a)
Usambara	576-634	Maboko (2000)

Slow Cooling Versus Multiple Events

One of the most intriguing aspects of the post-metamorphic thermal history of the MB is the very low cooling rates (1 - 4°C/Ma) recorded by various chronometers (Maboko *et al.* 1989, Maboko & Nakamura 1995, Moller *et al.* 1994). Following peak granulite facies temperatures of 840±40 °C at 630-700 Ma, the Eastern Granulites did not cool to temperatures of ~300°C until about 480 Ma ago in the Wami River area (Maboko *et al.* 1985), ~540 Ma in the Usambara Mountains (Maboko 2000b) and ~490 Ma in the Uluguru Mountains (Maboko *et al.* 1989). Such a protracted period of slow cooling, extending for a period of more than 230 Ma, is rather unusual even for deep crustal rocks like the Eastern Granulites. This observation prompted Maboko *et al.* (1985) to propose the existence of a younger, post-granulite event of crustal heating and resetting of mica isotopic systems in the Tanzanian sector of the MB. Isotopic evidence for such an event has, however, so far remained elusive. The 525-545 Ma granulite facies event recorded in the Kitumbi area therefore provides the first preliminary evidence for a post-Eastern Granulites metamorphism in the Tanzania sector of the MB, thus providing a plausible explanation for the rather unusual thermal history. Accordingly, it is proposed that the apparently low cooling rate inferred from a combination of zircon U-Pb and mica Rb-Sr and/or K-Ar ages are a result of an episode of a re-heating event which affected most of the eastern part of the MB during the ~530 Ma metamorphic event recorded in Kitumbi. This re-heating may have resulted in the partial opening of isotopic systems with low closure temperatures like the mica K-Ar and Rb-Sr systems. As pre-530 Ma biotite Rb-Sr ages are preserved near the western margin of the MB away from shear zones (Maboko 2000b), the effect of such re-heating in that part must only have been localized to areas of intense deformation. Assuming typical peak granulite facies metamorphic temperatures of ~700 - 800°C for the Kitumbi rocks and total resetting of the biotite Rb-Sr chronometer during the event, we can use the ~470 Ma biotite ages recorded from the eastern part of the MB (Maboko 2000b), and a ~300°C closure temperature for the Rb-Sr system (Jager 1979), to calculate a mean post-Kitumbi cooling rate of ~6 - 8°C/Ma. Such cooling rates are more realistic immediately after high grade metamorphism than the 1-4°C/Ma rates inferred from pooling together peak metamorphic ages from the Eastern Granulites and cooling ages from chronometers with relatively low closure temperatures.

Implications for Models of Gondwana Assembly

The existence of a regional granulite facies event at ~530-550 Ma offers a way of reconciling the palaeomagnetic and petrological/geochronological evidence for Gondwana assembly. Thus, as has been earlier proposed by Meert *et al.* (1995) the more common 630-700 Ma old granulite facies metamorphism found in most parts of the MB probably records regional crustal thickening arising out of collision of India, Madagascar, parts of Easten Antarctica and the Kalahari craton (IMSLEK terranes) with the Congo craton and the Arabian Nubian Shield (ANS). It is proposed that most of the metamorphic and structural characteristics of the MB were established during this event. The ~530-550 Ma granulites may then mark a younger, Kuungan, collision between Australo-Antarctica and the combined IMSLEK-Congo-ANS collage marking the final assembly of Gondwana (Meert *et al.* 1995). The available structural, metamorphic and isotopic evidence suggests that the intensity of this event in the Tanzanian sector of the MB was relatively mild. The main effect of the collision appears to be confined to the formation of small enclaves of granulites such as those in the Kitumbi area and the updating of mica Rb-Sr and K-Ar systems in the eastern parts of the belt. The preponderance of such ages in Eastern Antartica and Sri Lanka, however, suggests that the second collision was the major force that shaped the Neoproterozoic geology in those parts.

CONCLUSIONS

Garnets from two samples of the Kitumbi granulites in the Mozambique Belt of north-eastern Tanzania yield Sm-Nd ages of 525±15 Ma and 545±15 Ma. At the 95% confidence level, these ages are younger than the 576±15 to 634 ±16 Ma (Mean 606±12 Ma) ages previously published from the more extensive Eastern Granulites. The Kitumbi garnets are therefore best interpreted as dating cooling from a granulite facies event that is distinctly younger than the 630-700 Ma event that produced the Eastern Granulites. The Kitumbi rocks occur as small enclaves not separated from the surrounding amphibolite facies gneisses by any obvious structural discontinuity, lack the continental margin geochemical signatures that characterise the Eastern Granulites and yield late Archean depleted mantle crustal formation ages, similar to those obtained from the surrounding gneisses. These characteristics suggest that, unlike the Eastern Granulites that are isotopically exotic slices emplaced onto the surrounding amphibolite facies gneisses, the Kitumbi granulites are products of ~550 Ma old in situ granulite facies metamorphism of the surrounding country rocks.

The existence of a regional granulite facies event at ~530-550 Ma offers a way of reconciling the palaeomagnetic and petrological/geochronological evidence for Gondwana assembly. Thus, as has been previously proposed by Meert *et al.* (1995), the 630-700 Ma old event that produced the Eastern Granulites may record regional crustal thickening arising out of collision of India, Madagascar, parts of Easten Antarctica and the Kalahari craton (IMSLEK terranes) with the Congo craton and the Arabian Nubian Shield (ANS). The younger granulite event recorded in the Kitumbi area could then mark a younger collision between Australo-Antarctica and the combined IMSLEK-Congo-ANS collage marking the final assembly of Gondwana. It also offers a possible explanation for the abnormally slow cooling rates in the MB that have been calculated by pooling zircon U-Pb and mica Rb-Sr and/or K-Ar ages from the Eastern Granulites. It is proposed that the 1-4°C/Ma cooling rates are a result of an episode of re-heating which affected most of the eastern part of the MB during the ~530 Ma metamorphic event recorded in the Kitumbi granulites. This re-heating resulted in the partial opening of isotopic systems with low closure temperatures like the mica K-Ar and Rb-Sr systems. Assuming typical peak granulite facies metamorphic temperatures of ~700 - 800°C for the Kitumbi rocks and total resetting of the biotite Rb-Sr chronometer during the event, we can use the ~470 Ma biotite ages recorded from the eastern part of the MB (Maboko 2000b), and a ~300°C closure temperature for the Rb-Sr system to calculate a mean post-Kitumbi cooling rate of ~6 - 8°C/Ma.

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